

**A BIOINSPIRED CONCEPTUAL DESIGN METHODOLOGY  
FOR BIOROBOTS**

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## **ABSTRACT**

### **A BIOINSPIRED CONCEPTUAL DESIGN METHODOLOGY FOR BIOROBOTS**

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PhD in Modeling and Design of Engineering Systems (MODES)

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The main aim of this thesis is to develop a Bioinspired Conceptual Design (BICD) methodology for design of biorobots. Within the context of the dissertation, a novel BICD procedure has been developed based on existing BID approaches and systematic engineering design steps. This procedure is applied on several case studies, namely a dog biorobot (BioDog) for walking and trotting, a cockroach biorobot (BioCoc) for climbing, a jumping (grasshopper) biorobot for jumping and a hybrid (dog and lobster) biorobot for walking. A BICD process has been developed using the implementation results. Classic DEVS (Discrete Event System Specification) coupled model is used to formally represent the BICD process in order to develop a BICD methodology.

The proposed BICD methodology transforms customer needs into a concept design of biorobot with clear and well-defined six design steps. In order to overcome the drawbacks of existing BIDs, the biological system analysis and the bioinspired transformation design steps have been considered in detail.

In this thesis, although four case studies have been implemented to demonstrate the BICD methodology, fourteen biological systems and twenty four locomotion types are investigated by using content analysis and/or observation methods. The literature survey has been used for the content analysis method, while an experimental set-up is used to analyze the biological systems for the observation method. Required knowledge on morphology, function and behavior of biological systems are obtained using a high speed camera. During the bioinspired transformation step, the knowledge about the biological system has been transformed systematically into knowledge about the biorobots and this knowledge is used to develop the concept design of biorobots.

Keywords: Bioinspiration, Bioinspired conceptual design, Bioinspired robots, Biorobots, Bioinspired design methodology

## ÖZ

### **BİYOROBOTLAR İÇİN BİYOESİNLENMİŞ KAVRAMSAL TASARIM METODOLOJİSİ**

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Doktora, Mühendislik Sistemlerinin Modellenmesi ve Tasarımı

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Bu tezin ana amacı biyorobot tasarımlarına yönelik olarak Biyoesinlenmiş Kavramsal Tasarım (BİKT) metodolojisi geliştirmektir. Tez kapsamında, varolan Biyobenzetim Tasarım (BİT) yaklaşımlara ve sistematik mühendislik tasarım adımlarına dayanarak yeni bir BİKT prosedürü geliştirilmiştir. Geliştirilen prosedür, köpek biyorobotu (BioDog) üzerinde yürüme ve tırısaya gitme, hamamböceđi biyorobotu (BioCoc) üzerinde tırmanma, sıçrama (çekirge) biyorobotu üzerinde zıplama ve melez (köpek- istakoz) biyorobotu üzerinde yürüme hareketleri için uygulanmıştır. Örnek çalışmalardan elde edilen geri bildirimler kullanılarak bir BİKT süreci oluşturulmuştur. Hedeflenen BİKT metodolojisini oluşturmak için geliştirilen BİKT süreci, Klasik Ayrık Olay Sistem Spesifikasyonu (AOSS) modeli ile modellenmiştir.

Önerilen BİKT metodolojisi, açık ve tam olarak tanımlanmış altı adım ile müşteri ihtiyaçlarını biyorobotun kavramsal tasarımına dönüştürmektedir. Varolan BİT'lerin eksik olan taraflarının giderilmesi amacı ile biyolojik sistem analizi ve biyobenzetim dönüşüm tasarım adımları bu tez çalışması kapsamında detaylı olarak incelenmiştir.

Tez çalışmaları sırasında BİKT metodolojisinin tüm adımları tam olarak her ne kadar dört örnek çalışma üzerinde uygulanmış olsa da, on dört farklı biyolojik sistem ve yirmi dört hareket tipi içerik analizi yöntemi ve/veya gözlem yöntemi kullanılarak incelenmiştir. İçerik analizi için literatür taraması yapılmış, biyolojik sistemlerin gözlemlenmesi için ise bir deney düzeneği kurulmuştur. Deneyler sırasında biyolojik sistemlerin morfoloji, işlev ve davranışları hakkında gerekli bilgiyi edinmek için hızlı kamera kullanılmıştır. Biyobenzetim dönüşüm adımında, biyolojik sistem hakkındaki bu bilgi sistematik olarak biyrobotun kavramsal tasarımı için gerekli olan biyrobot hakkındaki bilgiye dönüştürülmektedir.

Anahtar Kelimeler: Biyoesinlenme, Biyoesinlenmiş kavramsal tasarım, Biyoesinlenmiş robotlar, Biyrobotlar, Biyoesinlenmiş tasarım metodolojisi

**To my family**

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## NOMENCLATURE

A	Actuator
App	Appearance of the expected product
Be	Behavior(S)
BeBR	Behavior of biorobot
BeBS	Behavior of the biological system
BICD	Bioinspired conceptual design
BID	Bioinspired design
BR	Biorobot(S)
BrBS	Breeds of biological systems
BS	Biological system(s)
BSK	Biological system knowledge
$C_{ij}$	Controller alternatives
$C_k$	Concept alternatives
CBR	Concept of a biorobot
Co	Constraints
Cos	Cost
d	A state
D	Set of state names
DEVS	Discrete event system specification
DFD	Data flow diagram
DiBS	Dimensions of the biological system
e	Time elapsed since last transition
EIC	An external input coupling connecting external inputs to state inputs
EOC	An external output coupling connecting state outputs to external outputs
ES	Engineering structures
ESK	Engineering system knowledge
F	Form
FoLb	Set of forms of limbs
FPS	Frame per second
Fu	Function(S)
FuBR	Function of biorobot
FuBS	Function of the biological system
FuCo	Function and constraints
GUI	Graphical user interface
Heh	Height of the expected product
$I_2$	Set of information about species and breeds of biological systems which perform required function
$I_3$	Set of information about selected biological systems
$I_4$	Set of information about biological systems used in the engineering domain
$I_5$	Set of information about engineering structures
IC	An internal coupling connecting state outputs to state inputs

J	Joint
JoL	Set of joints of each paired legs
$k_i$	Keywords
K	Set of keywords
KBR	Knowledge about a biorobot(s)
KBS	Knowledge about a biological system(s)
$K_{in}$	Kinematic data
$L_i$	Left legs
LoC	Set of types of jointed-leg locomotion
LoL	Set of limbs of each paired legs
M	Material
$M_d$	Classic DEVS atomic model of a state
Mor	Expected morphology for a biorobot
MorBR	Morphology of the biorobot
MorBS	Morphology of the biological system
N	A system representation with classic devs coupled model formalism
$N_{BICD}$	A system representation of the bidd process in the classic devs coupled model formalism
Ne	Customer needs
NuL	Number of legs
OpE	Operational environment
PaL	Set of paired legs according to anatomic structure
PB	Problem-based
PFV	Photron Fastcam Viewer
Q	Total set
$R_i$	Right legs
Spe	Specified features of the biorobot
S	States
$S_1$	State of “task clarifying”
$S_2$	State of “biological system selecting”
$S_3$	State of “ biological system analyzing”
$S_4$	State of “ bioinspired transforming”
$S_5$	State of “ engineering structure generalizing ”
$S_6$	State of “ engineering structure selecting”
SB	Solution-based
SBS	Species for a biological system
Sce	Schedule
Siz	The size of the expected product
SoM	The structure of muscles
Sur	Surface
t	Time
ta(s)	Expiration time
Tep	Temperature
ToJo	Types of joints
WeBS	Weight of the biological system
Weh	Weight of the expected product
X	Set of inputs to the system
$X_d$	Set of inputs of a state
Y	Set of outputs to the system

$Y_d$	set of outputs of a state
$\delta_{\text{ext}}$	External transition function
$\delta_{\text{int}}$	Internal transition function
$\lambda$	Output function
$\sigma$	Expiration time of a state (as a state variable)

# **CHAPTER 1**

## **INTRODUCTION**

It is known that the nature is the most important source of inspiration for engineering materials, processes, methods, structures, tools, devices, mechanisms, and systems to foster engineering creativity and innovation at high level. Structural and operational perfection of biological systems are achieved through evolution, the nature being an experimental platform of science and engineering. The idea of inspiration, mimicking and/or imitation of natural systems have been initiating biomimetic and/or bioinspired design (BID) practice for engineering designers, thus leading the engineering design research activities towards developing a methodological approach in this area. It is known that creative and innovative products are emerged during the conceptual design phase of the engineering design process. Thus, a bioinspired conceptual design (BICD) process can be treated as the first step of a BID process and existing engineering design phases can be applied for the succeeding phases of the BID.

The aim of this thesis is to develop a BICD methodology for the design of bioinspired robots (biorobots). In the dissertation, development of a process of BICD methodology from procedure to methodology and its implementation on several case studies for jointed-leg locomotion are presented.

Chapter 1 introduces the fundamental issues on bioinspiration approach, objective and scope of the thesis. Related terminology about bioinspiration is reviewed in Section 1.1. Mechatronics and BID are considered together with the perspective of biorobots in the section. The objective of the thesis is stated in Section 1.2. In

Section 1.3, scope of the thesis is described. Finally, organization of the following chapters based on the research organization is given in Section 1.4.

## **1.1 BIOINSPIRATION**

### **1.1.1 What is Bioinspiration?**

The biological inspiration process was first brought to public attention as “Bionics” by Jack E. Steele in 1960. Jack E. Steele (1924-2009), an American medical doctor and retired US Air Force colonel, mentioned bionic as “the science of systems which have some function copied from the nature, or which represent characteristics of natural systems or their analogues.” as cited in [Bar-Cohen, 2006\_a; Anon, 2007]. The term of “Bionics” is synonymous with “Biomimicry” (from bios, meaning *life*, and mimesis, meaning *to imitate*), describing a tool for innovation [Biomimicry Guild, 2009]. Biomimicry aims to develop solutions that meet the needs of society by studying and mimicking the design and behavior of the nature [The Natural Edge Project, 2008]. According to Fleischer [1999], biomimicry bridges biological systems and artificial systems and is defined as the process of engineering inspiration, ideas or mechanisms (morphologies, functions and behaviors) from a natural system to create an artificial one.

Otto H. Schmitt coined the term “Biophysics” which is the base of “Biomimetics” in 1969 [Vincent et al., 2006]. Biomimetics, which is a biology-based technology [Vincent and Mann, 2002] is a philosophical approach that can lead to novel ideas and innovative solutions in engineering domain. The term Biomimetics is increasingly involved with emerging subjects of science and engineering [Bar-Cohen, 2006\_b] and is used interchangeably with “Bionics”, “Biognosis”, “Biomimesis” and “Biomimicry” Vincent and his colleagues [Vincent et al., 2006] and DTI report [Anon, 2007] concluded that biomimetics is synonymous with “Biologically inspired” and it is usually called “Bioinspired” Although all of these terms; biomimetics, biomimicry, bioinspired, or bionics are used to describe the same approach, in this dissertation, *Bioinspiration* is preferred to focus on inspiration of design ideas from biological systems and their implementation into design of engineering systems with special emphasis on mechatronics engineering.

### **1.1.2 Why is Bioinspiration Emerging as a Field of Research?**

It is well-known that biological domain is an unlimited source of inspiration for engineers. Inspiration from biological phenomena and inspiration based products and applications on human life, dating back to more than 3000 years, are not a newly emerging concept. A typical example is the insisted attempts of ancient Chinese people towards production of artificial silk [Vincent et al., 2006]. Later studies are El-Cezeri's creation of human-like mechanisms [Rosheim, 1994] and Leonardo da Vinci's imitation works of the flight of birds to develop a flying machine [Vincent et al., 2006].

However, creative power of the inspiration is ignored during 19<sup>th</sup> century and early 20<sup>th</sup> century because of the idea that scientific knowledge had advanced enough for realistic and realizable plans for machines [Delcomyn, 2007]. Increasing the number of bioinspired products proves that in the 20<sup>th</sup> century, using inspiration was again revealed. Many success stories like Velcro [Wilson and Rosen, 2010] and self-cleaning paint inspired from lotus [Vukusic, 2010], are well known products of bioinspiration and are published on the Internet for curious investigators. Recent studies focus on developing a design methodology based on the inspiration idea, process, structure, material, behavior and/or function of biological systems and implementing the methodology in engineering systems to increase creativity and novelty.

### **1.1.3 Mechatronics and Bioinspired Design**

Buur [1990] states that "Mechatronics is a technology which combines mechanics with electronics and information technology to form both functional interaction and spatial integration in components, modules, products and systems.". Mechatronic systems form a subset of artificial systems and they are hierarchically at the same level as mechanical, electrical and software systems [Buur, 1990]. Figure 1.1 displays the historical development of mechatronic systems.

As cited by Luo and Lin [2008], "mechatronic is developed toward more efficient, more convenient, more intelligent, more integrated and human-friendly." In the future, it is expected that mechatronic systems have the capabilities of reconfigurability, self-organization, self-repair, autonomous evolution and self-

replication [Luo and Lin, 2008]. The ultimate aim of the mechatronic systems is to produce more-intelligent, more-autonomous and more-robust systems.

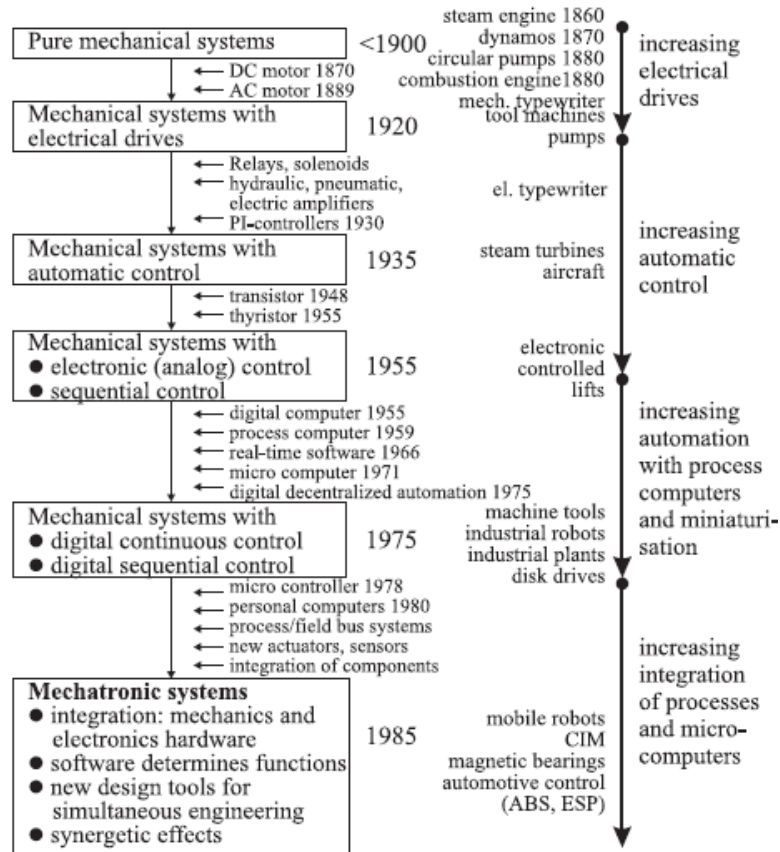


Figure 1.1 Historical development of mechatronic systems [Isermann, 2008]

To develop better mechatronic systems, bioinspiration plays a significant role [Luo and Lin, 2008]. Wooley and Lin [2001] cited that biology has potential roles as;

- source of principles (e.g., artificial neural network, fuzzy logic, genetic algorithm, expert systems and so on.),
- implementer of mechanism (e.g., a variety of mobile robots including wheeled robots, legged robots, flying robots, underwater robots, snake-like robots and other kinds of robots.),
- physical substrate for mechatronics (e.g., some bioimechatronic system, medical mechatronics, auxiliary mechanism for disabled human and so on.).

Meyer and Guillot [2008] stated that inspiring from biology is a new wave of robotics. Nowadays, design of robots inspiring from the nature is a challenging study

for engineers which is used to solve engineering/technological problems and satisfies needs of humanity with a creative and innovative approach. It is seen that the studies on BID in the engineering domain will continue rising because the progress of technology is endless.

A specific field of ongoing developments, design of the bioinspired robots (biorobots), is analyzed in the thesis studies. In literature survey, various biorobots designed with individual BID approaches are considered. However, existing BID studies of biorobots have not been discussed with a systematic design approach in the literature of design science. Moreover, required knowledge about a biological system model and transformation process of the knowledge from biological domain to engineering domain are still ad-hoc. Section 1.2 puts forth the objective of the thesis which arises from the described limitations.

## **1.2 OBJECTIVE OF THE THESIS**

### **1.2.1 Research Approach**

Recently, the state of the art of bioinspiration focuses on bioinspired design (BID) in order to develop a well-organized BID including a systematic mapping between biological and engineering domains. Current approaches on the BID can be divided into four key areas; biological and engineering research, representation of biological systems, analogical translation and design utilization as shown in Figure 1.2.

Most of the studies on the BID [Wilson, 2008; Mak and Shu, 2004\_b; The Natural Edge Project, 2008] stated that if an analogical translation is developed with a good bridge between biological and engineering domains, a better BID should be provided. This approach can be considered to be true but this kind of bridge is not sufficient to develop a more reliable/applicable BID. The studies on BID raise especially two important key points;

1. realistic representation of biological systems and
2. clarified and well-planned analogical translation.

Required knowledge about the biological system should be identified and the mapping, required to transfer the collected biological system knowledge into the engineering domain, should be developed with a representative model. These two

points are the missing points of the current BID processes. Hence, a necessity of developing a new BID methodology arises.

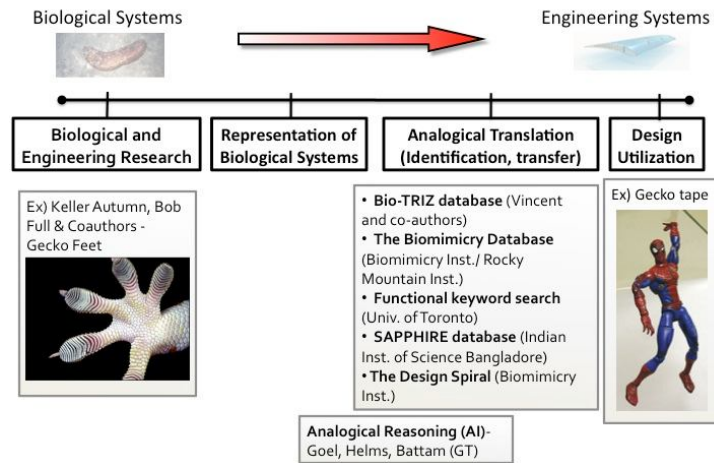


Figure 1.2 Current research on BID and four key areas of the BID [Wilson, 2008]

The fundamental reasoning behind the use of BID is to increase creativity (novelty and usefulness) and innovation in engineering. It is known that the main goal of any bioinspired design (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 design phase. Thus, the dissertation is focused on the bioinspired conceptual design (BICD) for the biorobots.

One of the limitations of the current BID studies is observed in the use of biological systems. The design process is applied by using one biological system. However, diverse functions, structures, and behaviors which are provided by multiple biological systems may be used for more creative bioinspired products. In the dissertation, the BID will provide opportunity to imitate multiple biological systems, if demanded or required. Thus, biorobots may include *hybrid biorobots*. The term of *hybrid biorobots* is preferred to indicate bioinspired robots which are combination of parts, features and/or ideas inspired from multiple biological systems. As an example, a grasshopper's leg for jumping and a bee's eye for vision may be integrated in a hybrid bioinspired robot.

### **1.2.2 Objective of thesis**

The overall aim of the thesis is to develop a BICD methodology for the design of biorobots. The methodology is developed to eliminate the limitations of the existing BIDs and provide a systematic design process for the design of biorobots. Thus, the BICD methodology should

- cover systematic methods/steps which are obtained from a biological system (or systems) to a concept of biorobot,
- represent a method to provide required knowledge about selected biological systems and
- supply a simple transformation step that transforms the knowledge from the biological domain to the engineering domain.

### **1.3 SCOPE OF THE THESIS**

The dissertation focuses on the development of an applicable BICD methodology to be implemented in the engineering design science. The implementation of the methodology is demonstrated on bioinspired robots (biorobots). Dog biorobot (BioDog), cockroach biorobot (BioCoc) and jumping (grasshopper) biorobot are some case-studies of the dissertation. Jointed-leg locomotion, such as walking and climbing is discussed as a motoric action in the case studies. Sensoric and cognitive actions are beyond the scope of the dissertation.

### **1.4 ORGANIZATION OF THE THESIS**

Research organization is shown in Figure 1.3. In the thesis, firstly, existing bioinspired design concepts, engineering design processes and their case studies/applications have been investigated. A proposal of a bioinspired conceptual design (BICD) procedure has been developed as the second step. Thirdly, the procedure has been implemented on several case studies. The BICD procedure is transformed in to a BICD process by using feedbacks obtained from the case studies. Fourthly, a BICD process model has been built by using the BICD process and modeling tools. A classic DEVS (Discrete Event System Specification) coupled model is selected to model the BICD process because of DEVS' systematic and

mathematical model structure which is appropriate to model a process. Then, the process model is applied on the same case studies. The research process has been completed when it is understood that case studies give reliable results. In the thesis, a BICD methodology is developed and proposed to engineering design science.

Figure 1.3 also represents organization of the thesis. Current BID processes, their applications and engineering design processes are summarized in Chapter 2. The philosophy of the developed BICD process is presented in Chapter 3. Details of each step of the process are also described in this chapter. Chapter 4 introduces the DEVS model of the BICD process. The case studies are represented in Chapter 5. Finally, the research activity and its output are discussed and governing conclusions are given in Chapter 6. Suggested further studies are also stated in the chapter as future work.

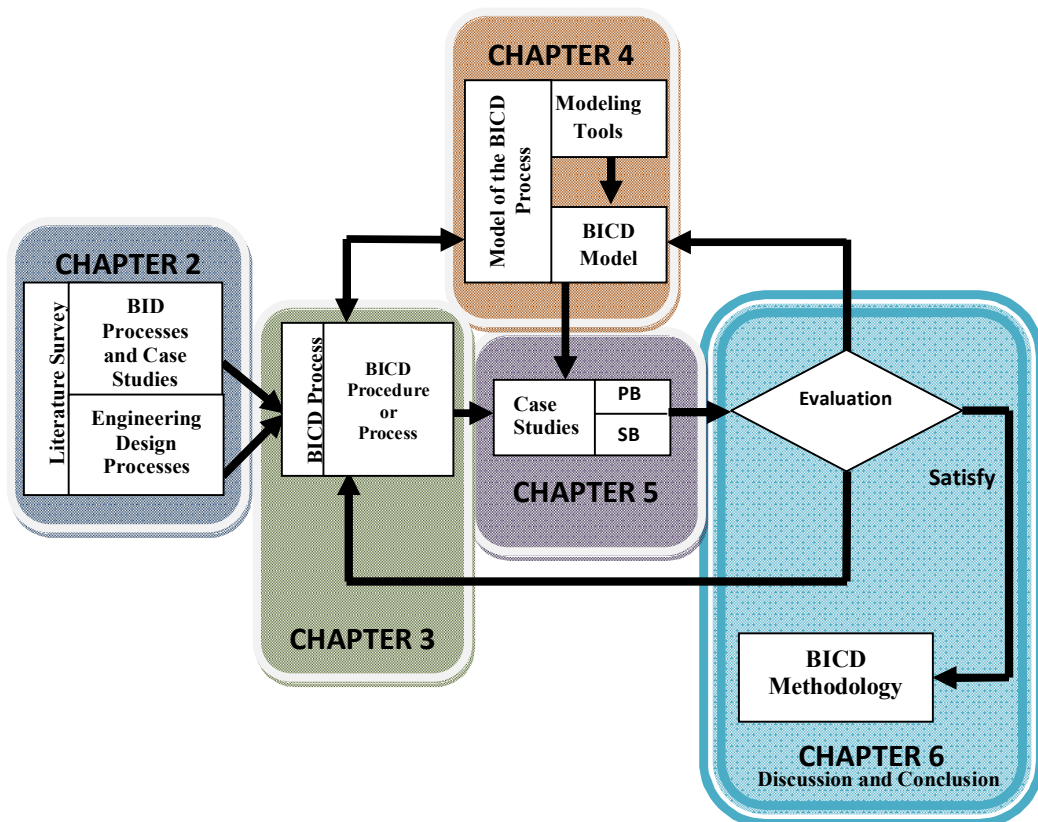


Figure 1.3 Organization of the research and the dissertation

## **CHAPTER 2**

### **LITERATURE REVIEW**

The idea of inspiration and/or imitation of natural systems have initiated bioinspired design practice for engineering designers, together with engineering design research to develop a methodological approach in the field of bioinspiration. After Chapter 1 that established the basic concepts on the topic, Chapter 2 reviews the current state of the topic and required background to develop a new BICD process for the design of biorobots. Bioinspired products including biorobots are considered in Section 2.1. Required terminology of engineering design and several existing engineering processes/methodologies are given in Section 2.2. Mechatronic design is also summarized in the same section. The concept of bioinspired design (BID), existing BID approaches and their applications and limitations are stated in Section 2.3. A general background about systems modeling necessary to model the BICD process is presented in Section 2.3.

#### **2.1 BIOINSPIRED PRODUCTS**

##### **2.1.1 Classification of Bioinspired Products**

Bioinspired products may be natural or artificial products. Artificial bioinspired products are inspired either from a part/ process/ structure/ function of biological systems (e.g. boe and walking) or from a structure built/made by biological systems (e.g. birds nest). When a biological system or a part of a biological system is directly used to develop a product fulfilling a defined task, the product is called a natural

bioinspired product. An example is a frog-like robot with real muscle tissues of a frog [Herr and Dennis, 2004].

It is proposed that bioinspired products can be classified into three groups. The first group includes bioinspired artificial products, which are inspired from biological systems. An example for this group is the artificial wings that were designed and tested by Hezarfen Ahmet Çelebi (1609-1640). He took off from the 56 m. tall Galata Tower near Bosphorus and landed successfully on Üsküdar with artificial eagle wings, using the force of the wind [Terzioğlu, 2007]. A similar work of artificial wings is a locus wing that helps to capture cracks as it is shown by researchers from Trinity College Dublin [Trinity, 2012]. This property is planned to be applied to buildings which will be highly resistant to earthquakes. Another artificial bioinspired product is the BigDog project of Boston Dynamics [Boston Dynamics, 2012]. They developed a robot named BigDog which can walk on its feet and carry heavy loads under rough terrain. Nowadays, researchers of the Boston Dynamics have completed a new version of the BigDog, Legged Squad Support System (LS3) [LS3, 2012]. They claim that “the goal of the LS3 program is to demonstrate that a legged robot can unburden dismounted squad members by carrying their gear, autonomously following them through rugged terrain, and interpreting verbal and visual commands.” An artificial bioinspired product is sometimes an algorithm or software. For instance, Bullock and his friends [Bullock et al., 2012] claim that they explore and extend a bio-inspired algorithm for collective construction influenced by paper wasp behavior. Some examples of artificial bioinspired products are given in Table 2.1.

The second type of bioinspired products are created by inspiration from structures which are built/made by biological systems. Examples are termite mounds, anthill and nests of birds which are grouped as architectural bioinspired products. Yiatros, Wade and Hunt [2007] cited that 30 St Mary Axe in London, the Commerzbank Tower in Frankfurt and the ACROS Building in Fukuoka City adopted natural ventilation strategies inspired from the structure of biological systems.

A bioinspired natural product, as a third type of bioinspired products, either is a biological system including some embedded electronic/mechatronic system or is an artificial system working with a real part of biological systems. Flying of a grasshopper [Shtull-Trauringi, 2012] and a moth [Daly, 2010], for example, are

controlled with embedded electronic components as an unmanned aerial vehicle. Another example is a frog-like robot whose actuators are real muscle tissues of a frog [Herr and Dennis, 2004].

Table 2.1 Examples of bioinspired products inspired from biological systems  
(Group 1)

<b>Biological systems</b>	<b>Inspired properties/ structures</b>	<b>Artificial Products</b>	<b>References</b>
Arctic species of fish	Ice-structuring proteins in the blood	Transportation system for ice-cream products	Vukusic, 2010
Birds	Wings	Ornithopter-type flying mechanisms	Terzioğlu, 2007; Vincent, et al., 2006
Boxfish	Aerodynamic structure	Bionic car	Vincent, et al., 2006
Burdock plant	Seeds hook	Velcro	Wilson and Rosen, 2010; Vukusic, 2010
Cat	Eye	Cat's eye reflector	Losic, 2011
Cockroach	Walking	Biorobot	Kingsley et al., 2003
Cricket	Climbing and walking	Biorobot	Quinn et al., 2001
Morpho Butterfly	Light and color (bio-optics)	L'Oreal LUCI range cosmetics	Vukusic, 2010
Butterfly	Light shimmer of its wing	Phone	Biotrue, 2012
Gecko	Surface on the feet	Adhesive tape	Hawken, 2006; Biotrue, 2012; Vukusic, 2010
Human	Eye	Multi-purpose solution (Bio-true)	Biotrue, 2012
Human	Leg	Prosthetic leg and exoskeletons	Kazerooni et al., 2007
Human	Trabecular struts in the head	Eiffel's tower	Vincent et al., 2006
Lobster	Eye	x-ray telescope	Vukusic, 2010
Locus	Wings	Building highly resistant to earthquakes	Trinity, 2012
Lotus	Water-repellant	Paint	Biotrue, 2012; Vukusic, 2010
Pinecones	Respond to extreme weather	Smart clothing	Anon, 2007; Biotrue, 2012
Trees	Branch	Stuttgart airport	Ahmeti, 2007
Turtle	Hard-shell body cover	Armor	Bar-Cohen, 2006 a
Waterlily	Leaf	Victorian Crystal Palace	Vincent et al., 2006
Whale	Bumps on its flipper	Whale-inspired fans	Biotrue, 2012

Within the scope of this dissertation, main focus is on the first group and particularly, bioinspired robots (biorobots) are considered. The developed BICD methodology is applied on the biorobots as case studies. Hence, in Section 2.1.2, biorobots are considered in detail.

### 2.1.2 Bioinspired Robots (Biorobots)

Biorobots are bioinspired robots which focus on the application of biological ideas to address technological problems [Beer, 2009]. Robots can be classified and investigated according to their sensoric (sensors), motoric (actuators) and cognitive (control architecture) components. It is known that a biorobot is at the intersection of biology and robotics [Beer, 2009; Webb, 2001]. Hence, biorobots can be considered with morphology, sensors, actuators, and control architecture. Meyer and Guillot [2008] proposed a similar classification for the biorobots. Their classification is given in Figure 2.1 with the additional gripping motion of actuators group.

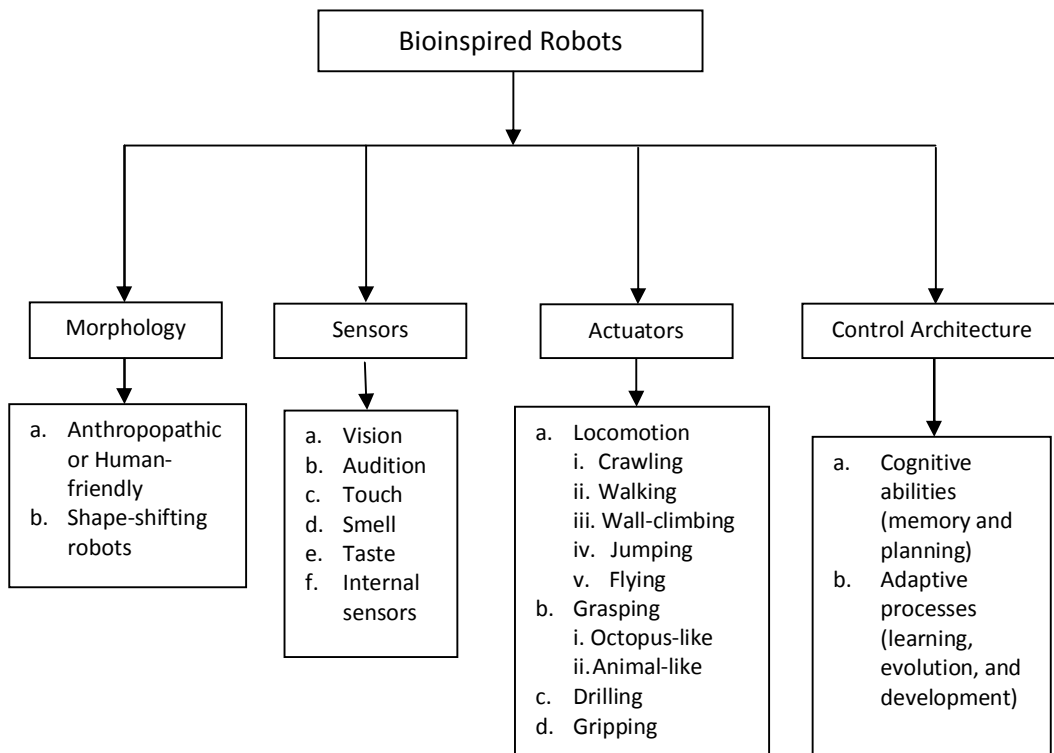


Figure 2.1 Classification of bioinspired robots

Bioinspired morphology, sensors, actuators, and control architectures shown in Figure 2.1 are described in following paragraphs.

*Bioinspired Morphology:* The meaning of morphology in any dictionary is given as the size, shape, and structure of an organism or one of its parts. Meyer and Guillot [2008] cited that the morphology of a bioinspired robot is considered with its functions and is grouped under two robot types; anthropopathic or human-friendly

robots and shape-shifting robots. Anthropopathic or human-friendly robots have a human-robot interaction. Shape-shifting robots can reconfigure their morphology according to internal or external circumstances.

*Bioinspired Sensors:* All living organisms have biological sensors and the sensors, which are inspired from these biological sensors, can be utilized in bioinspired robotic applications. There are two types of sensors used in bioinspired robotics; external and internal sensors. External sensors, such as vision, audition, touch, smell, and taste provide information about the environments of an animal or a robot while an internal sensor gives information about the robot's internal state.

*Bioinspired Actuator:* Locomotion, grasping, drilling and gripping are discussed under the title of bioinspired actuators. Locomotion of bioinspired robots involves crawling (worm-like and snake-like), walking, wall-climbing, jumping, swimming, flying and similar locomotion types. In grasping type of actuators provide two motions, octopus-like and animal-like. An octopus uses all the flexibility of its arms to reach food while an animal bends its flexible arms by using joints such as elbow when feeding.

*Bioinspired Control Architecture:* Cognitive architectures and adaptive mechanisms like learning, evolution and development are described into bioinspired control architecture. Behavior-based robotics, learning robots, evolving robots, and developing robots are represented as a part of bioinspired control architecture.

Several examples of biorobots, classified according to the above components, are tabulated in Table 2.2 based on the study of Meyer and Guillot [2008].

In this thesis, the main aim is to develop a BICD methodology for the design of biorobots. As stated in Chapter 1, in order to provide a systematic BICD methodology, the engineering steps are put into consideration. Section 2.2 represents required terminology of the engineering design and explains the systematic engineering design process. Since the expected output of the BICD methodology is to develop the concept of biorobots, mechatronic design is also summarized in the same section.

Table 2.2 Several examples of bioinspired robots

Group	Subgroups		Product Name	Developed at	Inspired from
Morphology	Anthropopathic or Human-friendly		Kismet	MIT	Human
			WE4RII	Waseda University	Human
			Uando	Osaka University	Human
	Shape-shifting		Concro	Polymerphic Robotics Lab. At USC-ISI	Snake-Insect
Sensors	Vision		Opto-electronic devices	Marseille's Biorobotics Lab.	Housefly
			DB's head	ATR	Human
			HRP2	Manufacturing Science and Technology Center (MSTC)	Human
			ASIMO	Honda	Human
	Audition		Khepera	University of Edinburgh	Cricket
			CIRCE	European Community (EC)	Bat
			Rodolph	Yale University	Bat-Dolphin
	Touch		Sprawlette	Stanford University	Cockroach
			Flexible Artificial Skin	Tokyo University	Human
	Smell		Robolobster	Brooklyn College	Marine animals
			WE4RII	Waseda University	Human
	Taste		Tasting robot	NEC System Technologies	Human
			Sommelier Robot	NEC System Technologies	Human
	Idiothetic		Cog robot	MIT	Human Baby
	Actuators	Crawling (Worm-like and Snake-like)		AmphiBot	EPFL
BIOLOCH				European Community (EC)	Undersea Worm
Walking (Biped, quadruped)		Cricket robot	Case Western University	Cricket	
		Big Dog	Boston Dynamics	Dog	
		RunBot	Stirling University	Human	
		Scout II	McGill University	Human	
Wall-climbing		Stickybot	Biomimetic Dextrous Manipulation Lab., Stanford University	Gecko	
		RiSE robot	DARPA Bionototics Program	Sinister killing robots	

## 2.2 ENGINEERING DESIGN

Cross [2001] explains the engineering design as a form of skilled behavior. Learning any skill usually relies on controlled practice and the development of related techniques. As a methodological approach, the engineering design solves a particular class of large and complex problems [Hyman, 1998]. A more reliable definition is available from the ABET documents [ABET, 2009];

“Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.”

Engineering design, which is at the centre of two intersecting cultural and technical streams [Pahl et al., 2007], requires;

- judgment, creativity, and discipline [Dekker, 1995],
- intuition [Cross, 2001],
- systematic and intelligent generation of artifacts [Waldron and Waldron, 1996],
- evaluation of specifications for artifacts [Waldron and Waldron, 1996],
- consideration of alternative solutions and feasibility considerations [Hyman, 1998],
- detail system descriptions [Hyman, 1998].

Designers use creative abilities to synthesize alternative designs and related knowledge is obtained from the basic sciences, mathematics, and engineering sciences [Eggert, 2005]. To be a successful designer one must have an understanding of all the factors that develop an engineering product [Cullum, 1988]. According to Howkes and Abinett [1984] and Cross [2001], a successful designer should;

- use “solution-focused” strategies when scientists use “problem-focused” strategies.

- identify the primary need for the product and then establish the secondary needs.
- clarify requirements,
- actively search for information,
- construct information on the problem formulation into requirements,
- be not suppress first solution ideas,
- detach themselves during conceptual design stages,
- produce variants but limit the production,
- be originator in the process of creating new products.

Engineering design can be classified into three groups [Evbuomwan et al., 1996] according to design problem types as shown in Figure 2.2. However, the classification of the engineering design with respect to design problems is tabulated differently by Eggert [2005] as given in Table 2.3.

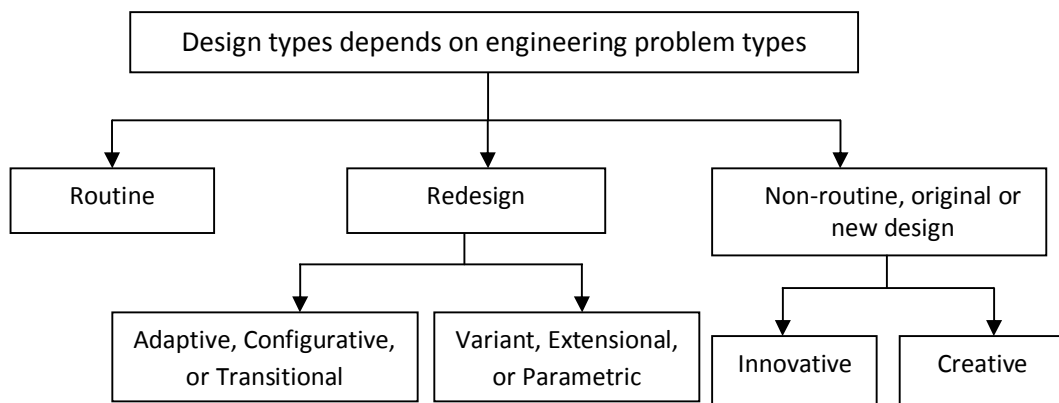


Figure 2.2 Design types according to design problems [Evbuomwan et al., 1996]

Table 2.3 Design types according to Eggert [Eggert, 2005]

Types of Design	Explanation
<i>Redesign</i>	modifying the “form”
<i>Selection design</i>	choosing from existing standard parts/subassemblies
<i>Variant design</i>	modifying existing part/subassembly, but keeping original concept
<i>Adaptive design</i>	adapting known solution to new task
<i>Original design</i>	new concept, part never existed before
<i>Artistic design</i>	modifying appearance or look

It is required that the terminology about method, methodology, process and procedure of design should be clarified before discussing the other background about engineering design. Section 2.2.1 explains the terminology.

### **2.2.1 Definitions of Procedure, Process, Method, and Methodology of Engineering Design**

The terms of design procedure, process, method, and methodology are defined in the following paragraphs.

*Design Procedure:* Eder and Hubka [1996] explained that design procedure is an individual way of a certain designer to perform a design task.

*Design Process:* Eder and Hosnedl [2008] stated that an engineering design includes a transformation process in which an object is transformed from one state to a preferably more desirable different state. Similarly, Eder and Hubka [Eder and Hubka, 1996] cited that design process is used to transform the information from the needs into a description of the designed technical system. In the dissertation, design process represents a systematic application of a design procedure in which knowledge in a specific domain is transformed to a target domain.

*Design Method:* Eder and Hubka [1996] defined that design methods are classified into two groups; strategies (guidelines and principles) and tactics (giving details of operations).

*Design Methodology:* Design methodology is a coordinated grouping of methods [Eder and Hubka, 1996]. Similarly, Evbuomwan, Sivaloganathan and Jebb [1996] evaluated the design theory as a collection of principles and described the design methodology as a collection of procedures/tools/techniques for designers. It describes *how to do design*. In addition, Ng [2006] claimed that “The ability of a design methodology to provide an indicator to a designer on how well his/her design process is progressing towards meeting its design requirements will be an important basis for intelligent design.” Section 2.2.2 summarizes the existing engineering design processes/methodologies.

### **2.2.2 Engineering Design Processes/Methodologies**

Design process is a systematic problem solving strategy. It is used to develop many possible solutions to solve a problem or satisfy needs and to narrow down the

possible solutions [Karsnitz et al., 2009]. The design process has an interval and in this duration, it includes periods of both convergence and divergence although in general it is convergent (Figure 2.3). Examples of existing engineering design processes are tabulated in Table 2.4 based on the study of Evbuomwan, Sivaloganathan, and Jebb [1996].

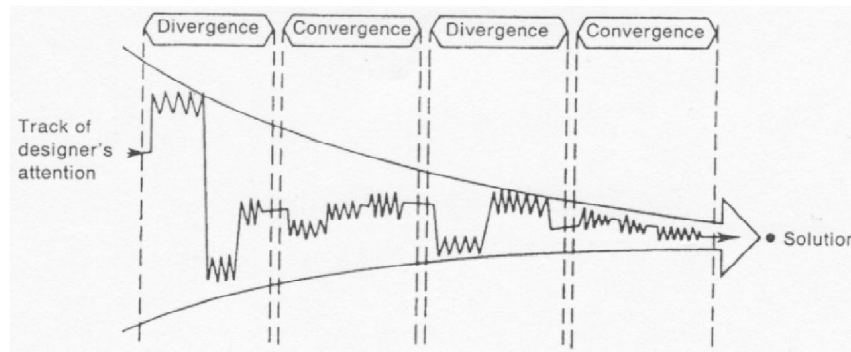


Figure 2.3 The overall design process [Cross, 2001]

In the thesis, engineering design is considered as a process with four phases; Task Clarification, Conceptual Design, Embodiment Design and Detail Design as cited in Pahl et al. [2007]. In this research, the main concentration is on the conceptual design phase. Steps of the conceptual bioinspired design were constructed by adapting the following steps, which are conceptual design steps in the engineering design process.

1. Clarify the task

In this step, customer needs are specified and organized in the form of a requirement list which covers required functions and essential constraints. The other steps are based on the requirements list.

2. Establish Function Structure

A function, performing tasks, includes a relationship between input and output of energy, material, and information. It is concerned with *what must be done*, rather than *how*. An overall function can be decomposed into sub-functions by using different methods. To bring out all system functions and function structures there are several methods. The function-tree method is one of them. It organizes the functions and sub functions around an overall function [Pahl et al., 2007].

Table 2.4 Examples of existing engineering design processes/methodologies with their phases and/or stages

	<b>Marples, 1960</b>	<b>Jones, 1962</b>	<b>Asimow, 1962</b>	<b>Watts, 1966</b>	<b>Krick, 1969</b>	<b>Pahl et al., 2007 (or 1971)</b>	<b>French, 1971</b>	<b>Harris, 1980</b>	<b>Archer, 1984</b>	<b>Hubka, 1992</b>	<b>Cross, 2001</b>
<b>Phase</b>	Synthesis		Feasibility study			Clarification	Analysis of the problem	Appreciation of the task	Analytical	Elaborate of assigned	
	Evaluation		Preliminary des.			Conceptual design	Conceptual design	Conception	Creative	Conceptual Design	
	Decision		Detail design			Embodiment Design	Embodiment of schemes	Appraisal of Concepts	Executive	Laying out	
						Detail Design	Detailing	Decision		Elaboration	
								Checking			
<b>Stages</b>		Analysis	Analysis	Analysis	Problem formulation	Define and clarify the task			Programming		Clarify objectives
		Synthesis	Synthesis	Synthesis	Problem analysis	Develop the principle solution			Data Collection		Establish functions
		Evaluation	Evaluation	Evaluation	Search	Develop the construction structure			Analysis		Set requirements
			Decision		Decision	Define the construction structure			Synthesis		Generate alternatives
			Optimization		Specification	Prepare production and operating documents			Development		Evaluate alternatives
			Revision						Communication		Improve details

### 3. Generate Solution Principles and Engineering Structures

The decomposed sub-functions are matched first with solution principles and their structures by using different methods. In this step, principle/structure alternatives are generated. In general, a morphological matrix [Pahl et al., 2007] tabulates the alternatives.

### 4. Evaluate Engineering Structures

A concept variant is a combination of the engineering structures gathered from the set of each sub-function alternatives. In this step, concept variants are developed. Then, a concept variant should be selected by using an evaluation method. In the literature, there are various methods for the selection. A few examples of evaluation methods are;

- Objective Tree [Pahl et al., 2007],
- Pugh's concept selection method [Eggert, 2005],
- Weighted Rating method [Eggert, 2005] and
- Mechatronic Design Quotient (MDQ) [Benbahani, 2007].

Objective tree, structured with evaluation criteria, provides a rating system to compare concept variants. Similarly, the Pugh's concept selection method and weighted rating method are based on comparison of concept variants according to evaluation criteria. MDQ is defined by Benbahani [2007] as "a multi-criteria index reflecting the overall degree of satisfaction of the design criteria for a mechatronic system." In addition, he added that the MDQ helps designers to select the best design choices. Also, the MDQ is based on a rating evaluation system.

In this study, concepts of the biorobots are considered. As a mechatronic product, in the design of biorobots, a specific point of engineering design, mechatronic design should be discussed. Section 2.2.3 summarizes mechatronic design.

#### **2.2.3 Mechatronic Design**

Although mechatronics is represented as an intersection of mechanics, electronics, software and control in general, Buur [1992] stated that design methodologies of machine design, electronic design and software design are not sufficient to design a mechatronic system. Isermann [2008] recommended a V-design model for mechatronic systems, including an interdisciplinary interface and this model is

shown in Figure 2.4 with the interpretation of Luo and Lin [2008]. In the V-model, the steps are classified into the mechatronic system design and system integration. The steps are considered separately for each engineering domain of mechatronics; mechanics, electrics (and electronics) and information to perform a required function.

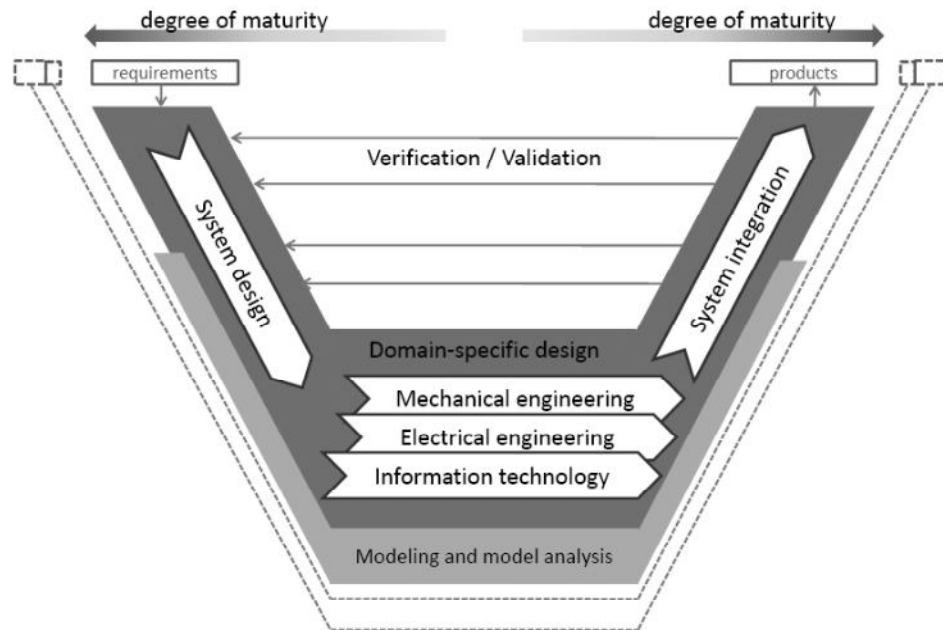


Figure 2.4 V-model design for mechatronic systems [Luo and Lin, 2008]

The main aim of this thesis is to develop a BICD methodology for the design of biorobots. As it was defined before, the biorobots are intersection of biology and robotics. In the robotics approach, the concept of engineering design and also mechatronic design are discussed in Section 2.2. It is clear that robotic applications in engineering domain or engineering design processes are not enough to design biorobots. Biology domain of the biorobots should also be considered. Thus, Section 2.3 presents the concept of BID and explains the existing BID processes. In this research, a systematic combination of engineering design and BID are accomplished for the design of biorobots.

## 2.3 BIOINSPIRED DESIGN (BID) STUDIES IN THE LITERATURE

### 2.3.1 Bioinspired Design (BID)

Wilson [2008] stated that “Bioinspired design is the transfer of design strategies used in the natural domain to the engineering domain. Leveraging biological technologies in the engineering domain can lead to many technological innovations and novel products.” Bioinspired design (BID) examines biological analogies to solve engineering problems [Mak and Shu, 2004\_b; Nelson, Wilson, and Yen, 2009]. The BID providing guideposts for creating [Fleischer, 1999] and a cross-over link between biological systems and engineering systems [The Natural Edge Project, 2008], has led to new and useful products and technologies [Vincent and Mann, 2002] and some of them have been patented [Anon, 2007].

### 2.3.2 Existing BID Approaches

In the literature, the BID process is typically classified into two groups according to its starting point. The first group is the “Problem-Based BID (PB-BID)” and the second is the “Solution-Based BID (SB-BID)” [Wilson, 2008; Helms, Vattam, and Goel, 2009]. In the PB-BID approach, a designer starts with an engineering problem and searches for possible and feasible solutions from biological domain. In the SB-BID, however, the design process starts with the recognition of a biological solution and the designer implements the principles of the existing solution in the biological domain to solve a problem in the engineering domain. Some case studies that use these two approaches are given in Table 2.5 [Konez Eroğlu et al., 2011\_c].

Table 2.5 Product examples which are designed by PB-BID and SB-BID approaches

BID Approach	BID Case Study	Phenomenon in the nature	Engineering Application
Problem-Based Design	A smart cloth [Anon, 2007].	Pinecones	A smart cloth (Textile)
	BigDog [Raibert et al., 2008]	A dog	Animal-like robot (big dog) (Robotics)
	Eiffel’s tower [Anon, 2007]	Trabecular struts in the head of the human femur or the taper of a tulip stem.	A tower (Architecture)
	A bionic car [Vincent et al., 2006].	The shape of the boxfish	A car (Automotive)
Solution-Based Design	Velcro [Wilson and Rosen, 2010]	Burrs	Velcro (hook and loop) (Textile)
	Gecko of University of Manchester [Hawken, 2006].	The natural hairs covering the soles of gecko’s feet	A new type of adhesive (Tribology and Robotic)
	Locus Wings [Trinity, 2012]	Wings of locus help to capture cracks	Building (Architecture)

An extensive literature survey has been performed to reveal available and published case studies of some PB-BID and SB-BID. The design cases have been further analyzed to determine the BID steps to understand the current state of technology. The results are presented in Table 2.6.

As observed in Table 2.6, the common steps of PB-BID are “problem definition”, “biological system selection”, “biological system representation”, and “implementation of the representation in engineering domain”. Similarly, the common steps of SB-BID are “biological system selection”, “biological system representation”, and “implementation of the representation in engineering domain”.

These models have some limitations, such as lack of mapping between biological and engineering domains and lack of clarity for the representation of biological systems. A suitable bridge between biological and engineering terminology is required to avoid wasting of time [Vakili and Shu, 2001]. This bridge is called as “Database” [Mak and Shu, 2004\_a]. There are few databases to assist designers and engineers in their searches, including *Biomimicry Guild Database* as an open-source database of natural organisms [The Natural Edge Project, 2008], *Biologists at the Design Table* (BaDTs) used to find species and organisms that might assist in design solutions [The Natural Edge Project, 2008]. *TRIZ* is another database study that is a method for transferring knowledge between different scientific and engineering disciplines [Vincent and Mann, 2002] by using contradiction Matrix [Vincent, 2001] including biological information and principles [Mak and Shu, 2004\_b].

In addition, a *database* of Max Planck Institute listing approximately 1,000 biological materials for particular applications [Anon, 2007] and a *lexical database* (WordNet) used as a language framework to systematically generate alternative keywords, (particularly verbs [Shu, 2006]) to find matches and analyze the results of searches [Chiu and Shu, 2004; Helms, Vattam, and Goel, 2009] can be given as examples of database studies. Other examples of databases are *SAPPHIRE* that provides English language descriptions of the structures, behaviors and functions of biological and engineering designs previously used in biomimetic design, a *diagrammatic representation* based on SAPPHIRE [Helms, Vattam, and Goel, 2009] and *Biomimicry Repository* which uses an ontology Description Logics [Wilson, 2008; Yim, Wilson, and Rosen, 2008]. Table 2.7 gives examples of these database packages.

Table 2.6 Examples of existing BID processes [Konez Eroğlu et al., 2010]

BID	Author(s)	BID steps (derived by thesis author)	Domains of Steps
PB	Helms, Vattam, and Goel [2009]	<ul style="list-style-type: none"> <li>➤ problem definition</li> <li>➤ reframe the problem (biologizing)</li> <li>➤ biological solution search</li> <li>➤ define the biological solution</li> <li>➤ principle extraction</li> <li>➤ principle application</li> </ul>	<p>Engineering Engineering-Biology Biology Biology Biology-Engineering Engineering</p>
	The Natural Edge Project [2008]	<ul style="list-style-type: none"> <li>➤ identify the real challenge</li> <li>➤ translate the challenge into biology language– ‘Biologise’ the question</li> <li>➤ define the habitat parameters/conditions</li> <li>➤ re-ask ‘How does the nature do that function here, in these conditions?’</li> <li>➤ find the best natural models (literal and metaphorical)</li> <li>➤ mimic the natural model as form, process, and ecosystem</li> <li>➤ evaluate the solution – the nature as measure</li> <li>➤ pay respect to the Inspiration</li> </ul>	<p>Engineering Engineering-Biology  Biology Biology  Biology  Biology-Engineering  Engineering Engineering</p>
	Biomimicry Guild [2009]	<ul style="list-style-type: none"> <li>➤ distill (distill the design function)</li> <li>➤ translate (translate to biology)</li> <li>➤ discover (discover natural models)</li> <li>➤ emulate (emulate the natures strategies)</li> <li>➤ evaluate (evaluate your design against life’s principles)</li> </ul>	<p>Engineering Engineering-Biology Biology Biology-Engineering Engineering</p>
	Anon [2007]	<ul style="list-style-type: none"> <li>➤ formulate the technical problem</li> <li>➤ seek for analogies in biology</li> <li>➤ identify corresponding principles</li> <li>➤ abstract from the biological model</li> <li>➤ implement technology through prototyping and testing.</li> </ul>	<p>Engineering Biology Biology Biology-Engineering Engineering</p>
SB	Vakili and Shu [2001]	<ul style="list-style-type: none"> <li>➤ select initial information source of biological phenomena</li> <li>➤ identify of synonyms for engineering functional keywords</li> <li>➤ identify of suitable bridge between engineering functional keywords and synonyms and biological phenomena</li> <li>➤ search for keywords and synonyms in bridge</li> <li>➤ identify and find more detail on relevant biological phenomena</li> </ul>	<p>Biology  Biology  Biology-Engineering  Biology-Engineering Biology</p>
	Anon [2007]	<ul style="list-style-type: none"> <li>➤ identify a biological system</li> <li>➤ analyze biomechanics, functional morphology and anatomy</li> <li>➤ understand the principles</li> <li>➤ abstract from the biological model</li> <li>➤ implement technology through prototyping and testing</li> </ul>	<p>Biology Biology  Biology Biology-Engineering Engineering</p>
	Helms, Vattam, and Goel [2009]	<ul style="list-style-type: none"> <li>➤ identify of a biological solution</li> <li>➤ define of the biological solution</li> <li>➤ extract of a principle</li> <li>➤ reframe the solution</li> <li>➤ search a problem</li> <li>➤ define of the problem</li> <li>➤ apply of the principle</li> </ul>	<p>Biology Biology Biology Biology Biology-Engineering Engineering Engineering</p>

Table 2.7 Existing database tools

Database	Researchers	Applied to	Searchable information	Search tools	Detail	Reference
Biologists at the Design Table (BaDTs)	Biomimicry Guild	Natural Systems (species and organisms)	The nature's strategies	Web-site	Biologists who move easily from biology to business, taking complex biological data and translating it into language digestible by any department, from marketing to R&D.	Biomimicry Guild, 2009
SAPPhIRE	Indian Institute of Science at Bangalore	Natural and Artificial Systems	<ul style="list-style-type: none"> <li>- Functions</li> <li>- Structures</li> <li>- Behaviors</li> </ul>	A software, IDEA-INSPIRE represented using natural language format using <ul style="list-style-type: none"> <li>- Nouns</li> <li>- Verbs</li> <li>- Adjectives/Adverb</li> </ul>	<ol style="list-style-type: none"> <li>1. Design problems are given in the V-N-A triplet form.</li> <li>2. Software matches them with the selected variables from the computer-interpretable form of the entries.</li> <li>3. The matched entries are then sorted in descending order of importance by the degree of matching found between the variables.</li> </ol>	Wilson, 2008; Chacrabarti, 2010
Functional Database	Bruck and co-authors	Bioinspired design concepts and products	<ul style="list-style-type: none"> <li>- Functional description templates</li> <li>- Repository of bioinspired concepts and products</li> <li>- Search tools</li> </ul>	<ul style="list-style-type: none"> <li>- Keyword search</li> <li>- Category filter</li> <li>- Function search</li> </ul>	In the keyword search, retrieval is performed using a string matching algorithm combining both equivalence and similarity methods. The category filter is then used to filter the results on the basis of product type, biological type, and development stage. The function search utilizes the keyword search algorithms to search for functions.	Wilson, 2008
Functional Keyword Search	University of Toronto	Biological resources already in natural language format to locate novel biological phenomena	<ul style="list-style-type: none"> <li>- Functional keywords search</li> </ul>	Wordnet, an electronic lexical database	<ol style="list-style-type: none"> <li>1. A user identifies the applicable functional keywords to search the database by using verbs</li> <li>2. The program determines dominant bio-phenomena</li> <li>3. The user then sorts through these results manually.</li> </ol>	Wilson, 2008 and wordnet: <a href="http://wordnet.princeton.edu/">http://wordnet.princeton.edu/</a>
Bio-TRIZ	Vincent and Mann	Natural and Artificial Systems	Functions or Contradictions of the design problem	TRIZ Contradiction Matrix	<ol style="list-style-type: none"> <li>1. Design problem are characterized as a pair of conflicting characteristics.</li> <li>2. They are matched to solution strategies from previously solved problems (3 million patents)</li> <li>3. Matrix is used to match the contradictions of the design problem to innovative solution strategies.</li> </ol>	Wilson, 2008
Biomimicry Database (Biomimicry Guild Database)	Rocky Mountain Institute and the Biomimicry Guild	Biological Information to identify biological analogs.	<ul style="list-style-type: none"> <li>- Challenges (problem that need to solve)</li> <li>- Strategies (potential solutions to the challenges)</li> <li>- Organisms (associated biological systems)</li> <li>- People (person/user records)</li> <li>- Citations</li> <li>- Products (associated bioinspired products)</li> </ul>	Web-site (no longer supported)	User uses keywords to search across all database records.	<a href="http://database.portal.mwest.com/db_intro_help.html">http://database.portal.mwest.com/db_intro_help.html</a>
Biomimicry GUI (Repository)	Wilson and Rosen	Natural and Artificial Systems	<ul style="list-style-type: none"> <li>- Flows (Input/Output)</li> <li>- Behaviors (Action/Attribute)</li> <li>- Structure</li> <li>- Domain (Bot/Bio/Eng)</li> <li>- System Strategy</li> </ul>	A software depends on ontology and its description logic by using Protégé, RacerPro, DIG interface	<ol style="list-style-type: none"> <li>1. Using the information, the designer selects defined keywords in the program.</li> <li>2. Solution alternatives are listed by the program.</li> <li>3. The designer compares these alternatives manually and selects one of them.</li> </ol>	Wilson, 2008

### 2.3.3 Limitations of Existing BID Methods

Survey of the related literature implies that there are some limitations in the existing BID processes and these limitations prevent their wide-spread use of these BID processes. The problems are originated for two main reasons; one of them is the “technology transfer” problems [The Natural Edge Project, 2008; Vincent et al., 2002; Helms et al., 2009] between biological domain and engineering domain, and the other is the limitations of existing BID methodology. Some of these limitations are listed below;

- Current BID processes are still *ad-hoc*.
- Current BID processes rely mostly on (personal/individual) experience of designers.
- Although existing literature suggests tools and/or systematic methods for the selection of biological systems to inspire, most of them provide only keyword translation between the two domains.
- PB-BID and SB-BID approaches are similar in nature; however, different steps are applied.
- 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 clear, systematic and standard approach for sound and practical applications.
- Most of the published studies claim that one biological system is used to be inspired for a bioinspired product. This limited number delimits the design variety and creativity. However, multiple biological systems can be used for inspiration of a bioinspired product.

These limitations enforce to perform new studies on BID. In the dissertation, the objective is to overcome these limitations by developing a systematic BICD methodology. With this aim, firstly, a procedure is structured based on well-known engineering design steps and the existing BID steps. Secondly, the procedure is translated into a process with well-defined and well-organized steps. All these steps are applied on biorobot case studies and after the evaluation of the results obtained

from the case studies, the procedure and the process are updated. In conducting case studies, main concentration is on the jointed-leg locomotion as motoric action. Sensors and control architecture are beyond the scope of the thesis. Finally, the process is modeled by using a method of system modeling to develop the BICD methodology. Section 2.4 presents background information about the system process modeling techniques required to model the BICD process.

## 2.4 SYSTEM MODELING

A *model* may represent a system (e.g., a manufacturing system), an object (e.g., designed artifact), or a problem (e.g., designing a shaft) and is typically constructed for the purpose of analysis [Kusiak, 1995]. Haefner [2005] stated that systems can be discussed by using models. Similarly, Fishwick [1995] explained that “A model is something that we use in lieu of the real thing in order to understand something about that thing.”

Modeling is a never-ending process and the model always is revised and tested. Although Fowler [1997] stated that there is no *unique/correct model* of a system, Webb [2001] said that *good and bad models* relative to the purposes of the model builder can be considered. In the literature, different models and their classifications are considered. As an example, Fishwick [1995] classify models into five types as shown in Figure 2.5.

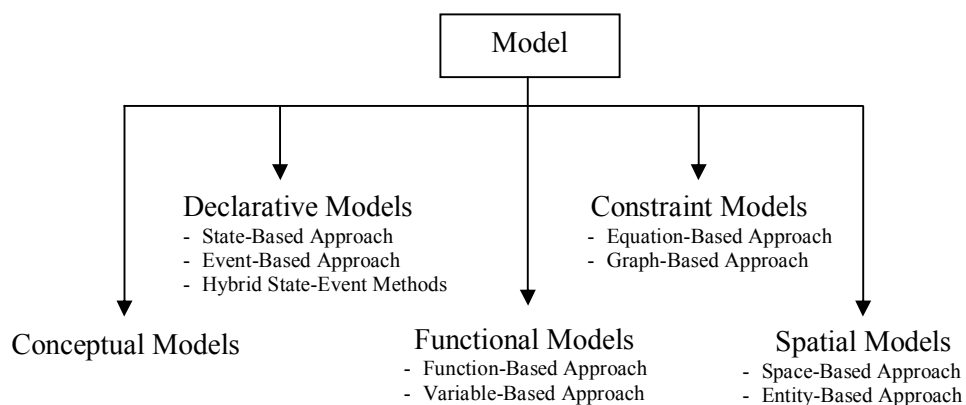


Figure 2.5 Model Classification of Fishwick [Fishwick, 1995]

Fishwick [1995] explained the models, given in Figure 2.5, as follows.

*Concept Models* are used to define physical systems at a very high abstraction level. A conceptual model emphasizes objects and their relations to one another. The creation of a concept model is an early stage of modeling in engineering design. Statement as a text model can be transferred into concept graphs and then they can be programmed by using different software languages.

In *Declarative Models*, the design concentrates on the form of the current system state and a subsequent system state after a state transition occurs. There are three approaches for these models: State-based, Event-based, and Hybrid state-event approaches. Heuristics for employing declarative models are:

1. If the system has discrete states or events, specify them using a declarative model.
2. If there are phases of a process, use a declarative model to model phase transitions. Phase transitions can be temporal or spatial if the spatial regions are irregular.

*Functional Models* are graphs containing two primary components: functions and variables. These models focus on functions that transform inputs into outputs while, normally, keeping track of a state vector along the way. Functional models are suited for representing systems that have coupled subcomponents- such as machines and plants. Some heuristics are the following:

1. If the problem is given in terms of distinct physical objects which are connected in a directed order, use a functional model.
  - a. If the objects are primarily functional in nature, use the function-based approach.
  - b. If the objects basically represent capacitance or storage, use the variable-based approach.
2. If the problem involves a material flow throughout the system, use a functional model.

*Constraint Models* are most useful to represent the laws of the nature -which are all symmetrical and amenable to being specified in terms of a balance of certain things. A balance may involve one of several different types of quantities –usually force, mass, momentum, or energy. In other words, these models present models as

collections of state variables that are related to one another in a constraint network. Constraint modeling, often in the form of equations, is appropriate when the underlying dynamics are based on conservation of some property such as force, mass, or energy. Although the usual form of a constraint network is a set of equations, there are other graph-based forms such as electrical networks and bond graphs.

Models that reflect a decomposition of space, usually with straight boundaries, are *Spatial Models*. These models focus on relating geometry directly to the dynamic model. Such models divide the world into many small pieces which interact in a geometrical fashion. Some heuristics to use when spatial modeling is chosen:

1. When the system is seen as many small, regular pieces. The pieces may fit together as in a jigsaw puzzle, or they may be particles which either map-to or approximate a physical phenomenon.
2. When you want to study a system in great detail. Normally, most spatial models are composed of a large number of pieces which divide the overall system geometry.

Similarly, Zeigler et al. [Zeigler et al., 2000; Zeigler et al., 2005] studied the modeling of systems. They model systems by using DTSS (Discrete Time System Specification), DEVS (Discrete Event System Specification), DESS (Differential Equation System Specification). These modeling types are displayed in Figure 2.6.

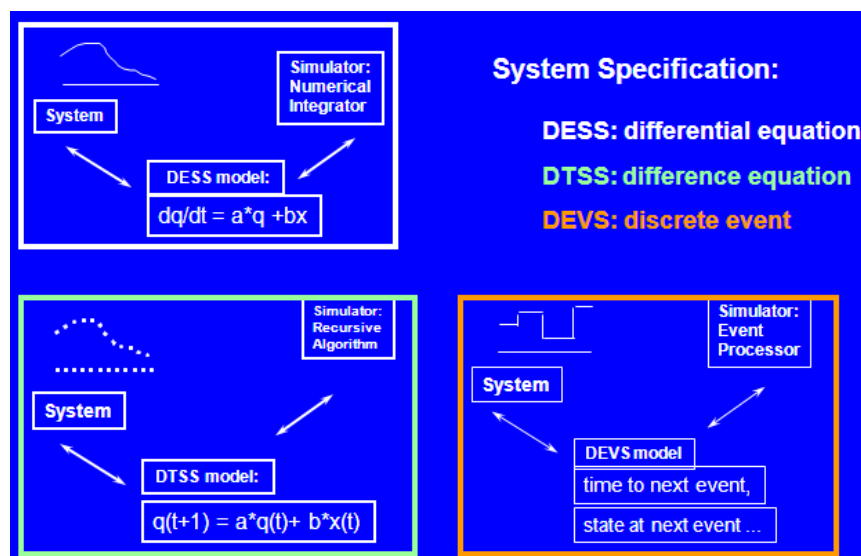


Figure 2.6 Representation of the DESS, DTSS and DEVS [Zeigler and Sarjoughian, 1998]

To build a discrete time model (DTSS), current state and input from the environment should be defined to determine the next state of the model. It may be said that the model describes how  $x_{n+1}$  depends on  $x_n$  if  $x_n$  is the current state and  $x_{n+1}$  represents the next state. In the DESS modeling approach, a state and an input value are assumed as given values and the rate of change of the state is only known. Next state can be computed by using this information. DEVS is a formalism for modeling of discrete event systems. DEVS is defined by Park and Leemis [2012] as a stochastic (some state variables are random), dynamic (time evolution is important) and discrete-event (significant changes occur at discrete time instances) model. In this study, DEVS modeling approach is used to model of the BICD process and the details are given in Chapter 4.

## **2.5 CHAPTER SUMMARY**

In this chapter, required background to develop a BICD methodology has been presented. Because of the overall aim of this dissertation, biorobots are described at the beginning of the chapter. Biorobots are intersection of two domains; engineering (robotics) and biology. In the aim of the BICD methodology, to decide the design process of the biorobots, engineering design and existing BID are investigated respectively. Terminology about engineering design, definition of bioinspired design and system modeling tools are considered in this chapter. Common engineering design steps and limitations of the existing BID processes are also demonstrated. In order to overcome the limitations of existing BIDs, a BICD methodology is aimed in this study. The model selection, required to develop the BICD methodology, will be considered in Chapter 4 after the BICD process are explained in Chapter 3.

## CHAPTER 3

### BIOINSPIRED CONCEPTUAL DESIGN PROCESS

The overall aim of this thesis is to develop a bioinspired conceptual design (BICD) methodology for the design of biorobots. In Chapter 3, the backbone of the proposed BICD methodology, which is the BICD process, is introduced. The exhibited philosophy of the BICD approach is summarized in Section 3.1. Section 3.2 represents the steps of the BICD process. The process steps are detailed in Section 3.3.

Chapter 3 and its place in the dissertation are illustrated in Figure 3.1. In the following sections, several symbols are used to abbreviate the sets. The abbreviations are tabulated in the List of Abbreviations.

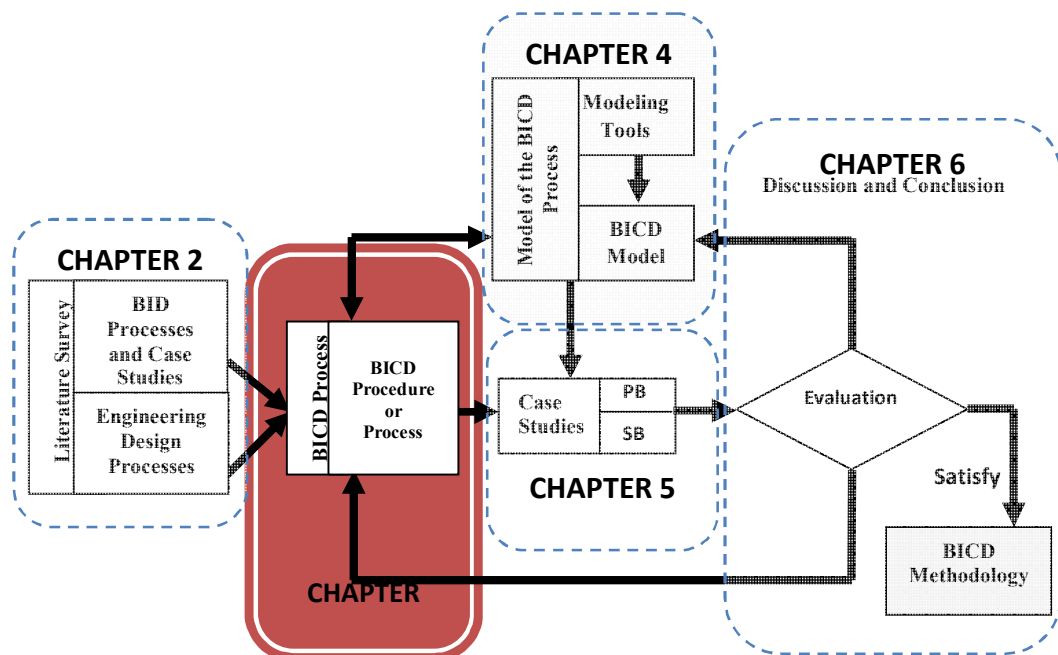


Figure 3.1 Chapter 3 and organization of the dissertation

### 3.1 THE PHILOSOPHY OF THE BICD APPROACH

The governing philosophy of the BICD approach is illustrated in Figure 3.2. The philosophy of the BICD is based on analogical reasoning similar to the existing BIDs, which were summarized in Chapter 2 [Helms et al., 2009; Mak and Shu, 2004\_b; Nelson et al., 2009; Tsujimoto et al., 2008; Wilson, 2008]. The analogical reasoning process begins with our existing biological system (BS) in the biological domain source domain and is completed with a biorobot (BR) design in the target domain which is the engineering domain. As shown in Figure 3.2, the biological system is analyzed to obtain knowledge about the biological system (KBS). Analysis of the biological system in the proposed BICD process is based on the definition of the analysis which is given in [Pahl et al., 2007] as “the resolution of anything complex into its elements and the study of these elements and their relationships” The knowledge is an appropriate collection of three pieces of information; morphology (MorBS), function (FuBS), and behavior (BeBS) about the biological system. These are discussed in Section 3.2.

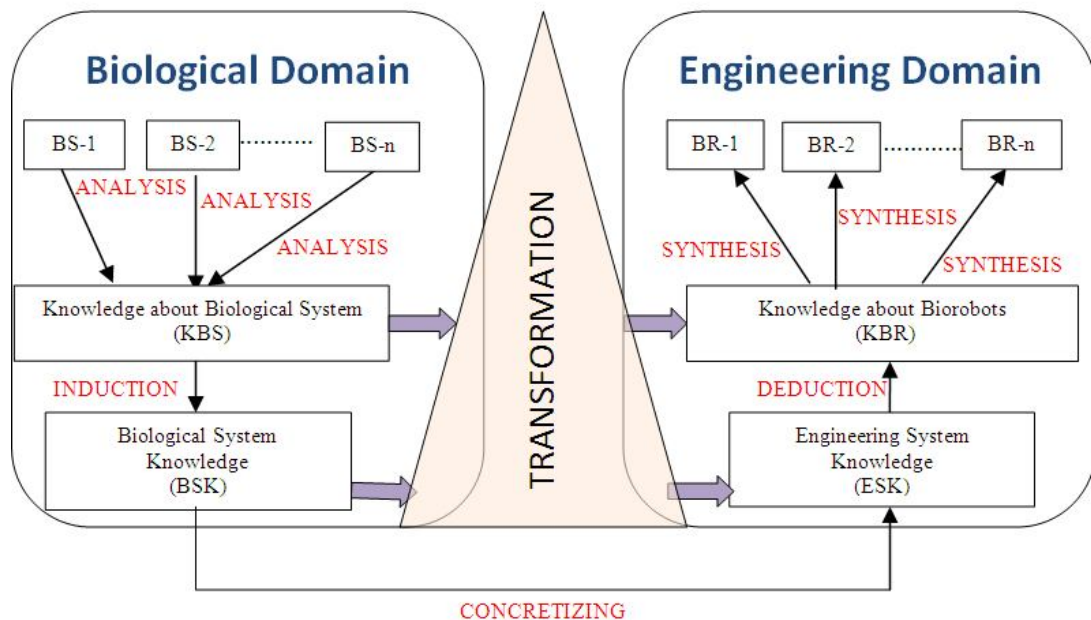


Figure 3.2 Philosophy of the BICD approach, BS representing a Biological System and BR a Biorobot.

The *KBS* is represented in Equation 3.1 where “i” is the number of biological systems or the number of different analysis results of a biological system. It means that *KBS*<sub>1</sub>, *KBS*<sub>2</sub>, and the other *KBS* may represent either different knowledge for the same biological system or the knowledge about completely different biological systems.

$$KBS_i = \{MorBS_i, FuBS_i, BeBS_i\} \quad i = 1, 2, 3 \dots n \quad (3.1)$$

If the number of analysis on biological systems is increased, a database of *KBS* will be created. In the dissertation, this database is referred to as Biological System Knowledge (BSK).

The induction is defined by Eder and Hubka [1996] as “going from experiences and observations towards definitions (of terms) and causes, from the particular to the general” Thus, *BSK*, represented in Equation 3.2, is obtained by an induction method. *BSK*, in Equation 3.2, is a set which includes knowledge about the n number of biological systems.

$$BSK = \{KBS_1, KBS_2, \dots KBS_n\} = \{KBS_i\} \quad i = 1, 2, 3 \dots n \quad (3.2)$$

This abstract structure of *BSK* is concretized to engineering system knowledge (*ESK*) which is represented in Equation 3.3. The concretizing, which is defined as “establishing a more concrete reality from a more abstract formulation” by Eder and Hubka [1996], provides a transformation of the knowledge from biological domain to engineering domain. Hence, *BSK* is transformed from the biological domain to the engineering domain, as *ESK*. As shown in Equation 3.3, *ESK* covers knowledge about biorobots (*KBR*).

$$ESK = \{KBR_1, KBR_2 \dots KBR_m\} \quad (3.3)$$

Equation 3.3 shows that the *ESK* will be decomposed into a *KBR* or multiple *KBRs*. This decomposition may be provided by a deduction method, which moves from the general to the particular according to Eder and Hubka [1996]. *KBR* is given in Equation 3.4 where “j” represents the number of biorobots and *FuBR*, *BeBR* and *MorBR* are respectively the function, behavior and morphology about any one of in biorobot (BR).

$$KBR_j = \{MorBR_j, FuBR_j, BeBR_j\} \quad j = 1, 2, 3 \dots m \quad (3.4)$$

As depicted in Figure 3.1, the *KBR* is synthesized by “proceeding from the parts to the wholes” [Eder and Hubka, 1996], to develop different or modified biorobots. Pahl and his colleagues [2007] claim that the synthesis is the fitting parts or elements together to produce new effects. In addition, they state that the association of components to form a whole is an essential feature of all design work.

Figure 3.2 shows two transformations from biological domain to engineering domain. The *KBS* can be transformed to the *KBR* and the *BSK* can also be transformed to the *ESK*. Although in this thesis, several biological systems are investigated and analyzed, it is clear that further investigations and analyses are required to discuss the *BSK*. Thus, the transformation from the *BSK* to the *ESK* is not considered in the current work. It is assumed that the bottom level of the process should be the *KBS* in biological domain and the *KBR* in engineering domain. When sufficient numbers of biological systems are analyzed, the induction and deduction may be accomplished in future. After presenting the overall philosophy of the BICD process its individual steps are introduced in Section 3.2.

## 3.2 THE BICD PROCESS

Bioinspired design (BID) for a biorobot is a topic of engineering design. As explained in Chapter 2, engineering design has four phases [Pahl et al., 2007]. A similar classification of design phases is given by [Eder, 1998]. These are Clarification, Conceptual design, Embodiment Design and Detail Design. Literature reveals that the only difference between a BID and a conventional engineering

design is observed in the conceptual design phase. Hence, in this study, the main focus is on the development of a systematic Bioinspired Conceptual Design (BICD) process. The other phases of the engineering design can be implemented directly on BID.

Figure 3.3 describes a general view of the BICD approach to design a hybrid structure using the methods of existing BID and that of the engineering design processes. The process is iterative and starts from a need (solution based BICD (SB-BICD)) or an engineering problem (problem based BICD (PB-BICD)). In this approach, the first step is “need analysis” in both SB-BICD and PB-BICD. SB-BICD starts with a need or idea including species of a biological system or systems. Thus, the output of the first step is biological systems for the SB-BICD. For the PB-BICD, the first step’s output is a set of keywords about the expected final product that is the biorobot.

The second step is decomposition and the other operations, in which a designer can follow two ways and selection of them depends on the BICD process type as SB-BICD and PB-BICD. In a PB-BICD, if the species of biological systems are unknown, those systems should be selected for this step. Then, for both SB-BICD and PB-BICD, biological systems are decomposed into biological elements/components. This decomposition should be performed by reverse engineering. At the end of this step, alternatives of biological systems components/elements (bio-elements) are obtained.

The third step is “selecting bio-elements” An appropriate variant of bio-elements is selected. The fourth step is “matching bio-elements with eng-elements” where bio-elements are matched with the corresponding elements in engineering domain. The output of the step is a set of engineering elements. Then, in the fifth step of “selecting eng-elements”, alternative engineering elements are used to develop concept variants for a biorobot using well known techniques of engineering design such as morphological chart. This step completes the whole BICD process and the cycle starts with needs or engineering problems.

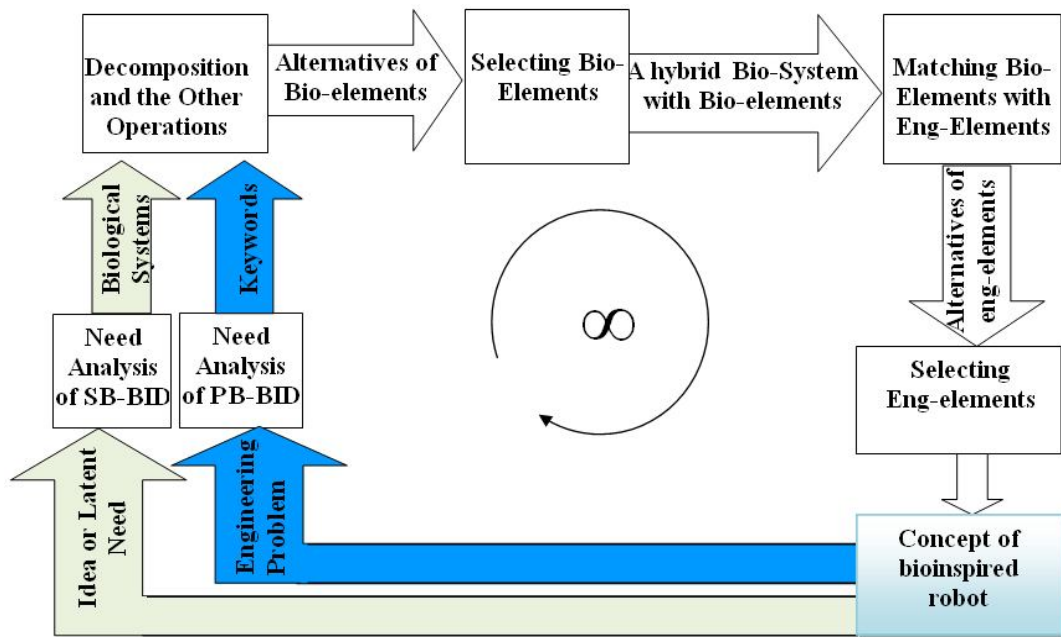


Figure 3.3 Representation of the approach in the BICD

Figure 3.4 represents the proposed BICD process and its distribution over the two design domains; the biological domain and the engineering domain. The process starts with a need independent from the characteristics of the design problem; that is, whether the design is PB and SB. The output of the process is a concept of a biorobot. The BICD process is composed of the following steps:

- Task Clarification,
- Biological System Selection,
- Biological System Analysis,
- Bioinspired Transformation,
- Engineering Structures Generalization and
- Engineering Structures Selection.

In the “Task Clarification” step required functions and essential constraints are identified using the problem statements. These functions/constraints are used as a basis for the following steps of the BICD process. In the next stage, “Biological System Selection”, a biological system or biological systems are selected based on the functions and constraints. Then, in the “Biological System Analysis” step, the selected biological system(s) is analyzed to collect required knowledge in terms of morphology, function and behavior. Then this knowledge is transformed from the

biological domain to the engineering domain during the stage “Bioinspired Transformation” Next, the transferred knowledge is matched with existing engineering structures/components in the “Engineering Structures Generalization” step. In the “Engineering Structures Selection” concept variants are developed for a biorobot. This final stage also includes selection of a convenient biorobot concept among these variants. These steps are explained in detail in Section 3.3.

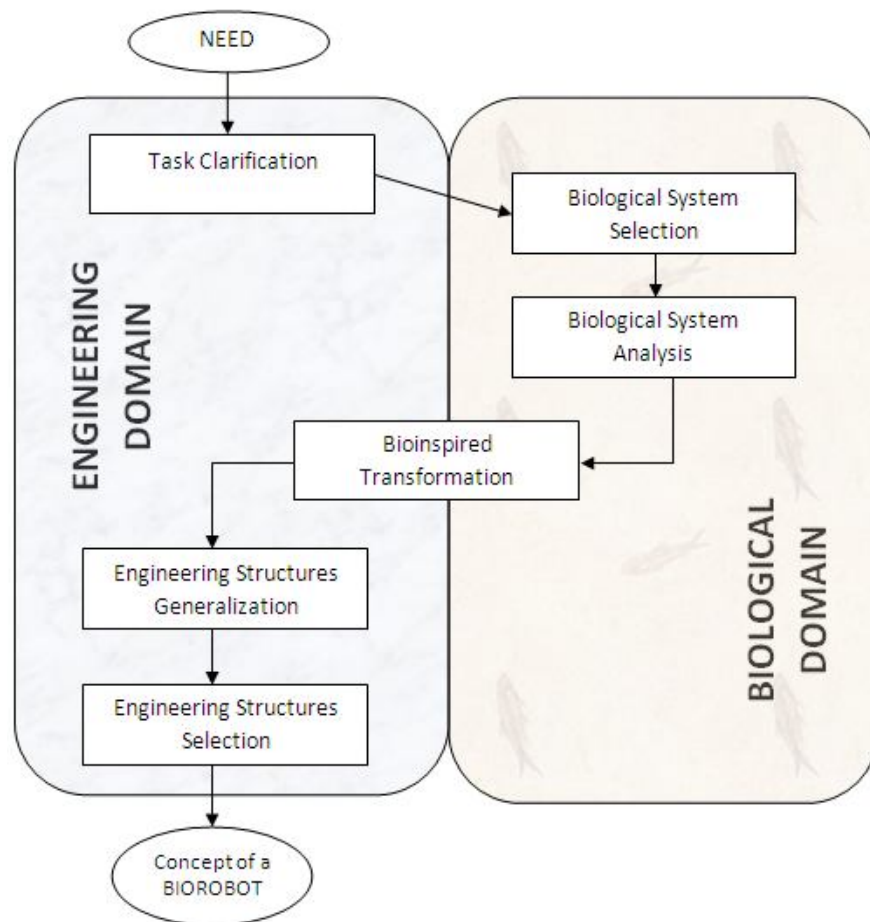


Figure 3.4 Steps of the developed BICD process

### 3.3 STEPS OF THE BICD PROCESS

This section gives detailed explanation for each of the six phases of the BICD process, given in Figure 3.4.

#### 3.3.1 Task Clarification

The first step begins with a customer need analysis and it is completed with the problem definition, including a set of function(s) and constraints. The task

clarification step includes two primary activities as shown in Figure 3.5. These are construction of a requirements list and problem definition including functional decomposition (if required). In the construction of a requirements list, customer needs are gathered and tabulated. Then, the problem is analyzed and defined by using the requirements list. The problem is stated with the required function(s) and constraints. Thus, at the end of this step, the function(s) and constraints are obtained regarding the design.

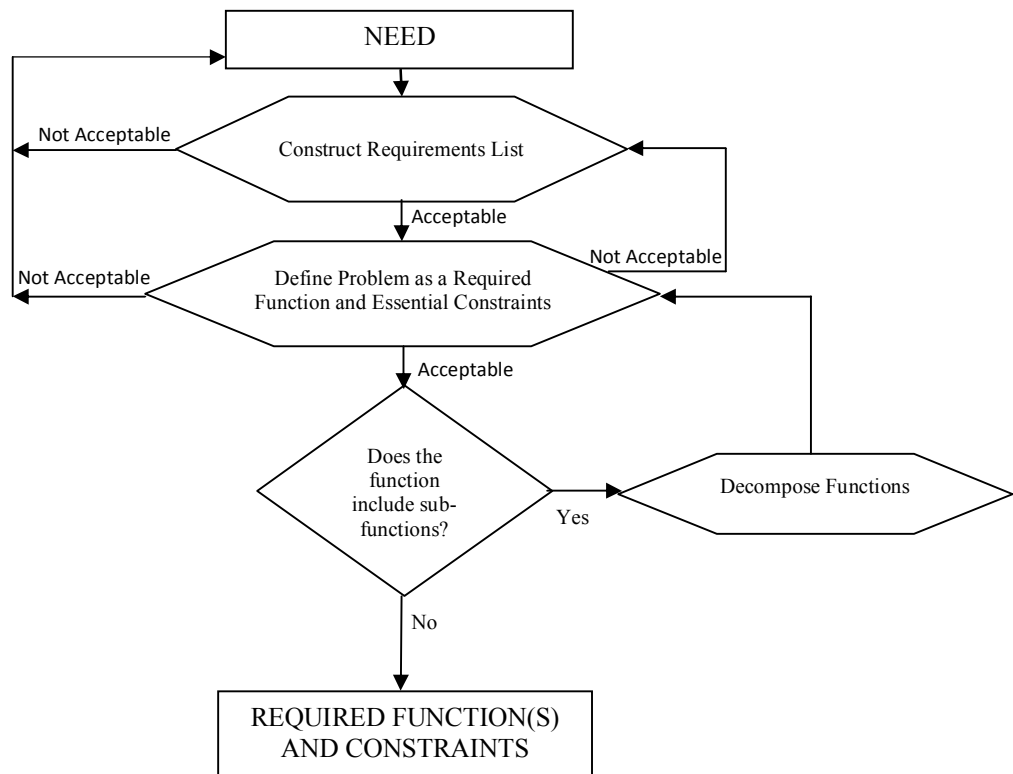


Figure 3.5 Sub-steps of the task clarification step

The scope of the thesis includes jointed-leg locomotion, such as walking, running, climbing and jumping and therefore, the locomotion types are considered as functions of the biorobot. In some situations, especially in the PB-BICD, the requirement function includes a few sub-functions. In that case, the function should be decomposed into sub-functions by using functional decomposition. As an example of such a function is “walk on different surfaces” This function can be considered as a combination of the following sub-functions: “walk on terrain surface”, “walk on smooth surface”, “walk in a stream environment (underwater walk)” After the

functional decomposition, constraints should be updated so as to include the sub-functions.

The functional decomposition may lead to a creative and innovative design. During the design, different biological systems may be selected for each sub-function. Thus, multiple biological systems are imitated to develop a biorobot which is called a *hybrid biorobot* in the dissertation. For example, to fulfill the function of “walk on different surfaces” the sub-functions may be matched with different biological systems. A dog can be matched for both “walk on terrain surface” and “walk on smooth surface” sub-functions, whereas a lobster may be selected for “walk in a stream environment (underwater walk)” sub-function. Such a matching may lead to the development of a biorobot concept whose walking behavior is a combination of a dog’s walking behavior and a lobster’s walking behavior.

As a result, the output of the task clarification step is required function(s) and constraints collected from the customer needs. A representative sketch of the task clarification is given in Figure 3.6. Details of the activities are given in the following sub-sections.

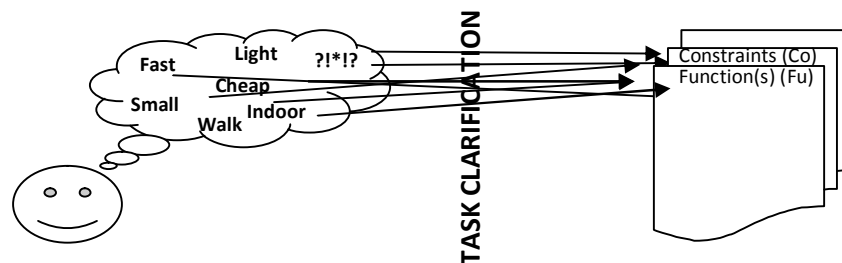


Figure 3.6 A representative sketch of task clarification

#### **i. Construct a Requirements List**

Task clarification step is used to determine requirements and existing constraints [Pahl et al., 2007]. For this purpose, a requirements list is prepared by using customer’s sentences. All design phases are based on this short-list. A requirements list for the BICD process is developed given in Table 3.1. This list is adapted from the requirements list suggested in [Pahl et al., 2007].

As given in Table 3.1, biorobots, 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 galloping. Sensoric sub-systems include vision, audition, touch, smell, and taste sensors which are imitated from the selected biological system(s). Cognitive sub-systems cover adaptive mechanisms such as learning, evolution, and control architecture. In the dissertation, only motoric action is considered as a functional characteristic of jointed-leg locomotion. Sensors and control architecture are beyond the scope of this dissertation.

Table 3.1 Example of a checklist for setting up a requirements list for a biorobot

<b>Main Headings</b>		<b>Examples</b>
<b>Species of the Biological System (if specified)</b>		Dog, Cat, Grasshopper, etc.
<b>Expected Morphology of the Biorobot</b>		Dimensions, size, weight, number of the links, appearance (desired vision), etc.
<b>Expected Function of the Biorobot</b>	<b>Motoric</b>	Locomotion, grasping, drilling, kinematic information such as velocity, acceleration, etc.
	<b>Sensoric</b>	Vision, audition, touch, smell, taste.
	<b>Cognitive</b>	Cognitive, adaptive, autonom, etc.
<b>Specified Features of the Biorobot</b>		Prescribed materials, source of energy, efficiency, friction, control equipment, modularity, etc.
<b>Operational Environment</b>		Surface roughness, operational temperature, etc.
<b>Cost</b>		Maximum permissible manufacturing cost
<b>Schedule</b>		End date of development, delivery date

The biological system (if there is), expected morphology and specified features of the biorobot together with operational environment and cost and schedule are also included in the requirements list.

## ii. Define Problem as a Required Function and Essential Constraints

After completing the BICD requirements list, the design problem is defined with the required functions and essential constraints. In this thesis, some example functions are walking, climbing and jumping. Constraints refer to the design limits. Expected

approximate dimensions of the biorobot or maximum permissible manufacturing cost can be given as examples of constraints.

Different from the approach of Pahl, Beitz and their colleagues [Pahl et al., 2007], if expected function of the problem includes hidden functions (sub-functions), it is necessary to decompose the expected function into sub-functions in the task clarification step of the BICD. This decomposition is only functions (i.e. walking, running) of the aimed biorobot. Decomposition can be done by known functional decomposition methods and after decomposition, the constraints should be updated.

The input/output relationship for the task clarification step is shown in Figure 3.7. In the figure,  $Ne$  represents a set of customer needs and  $FuCo$  is the set of functions and constraints. As represented in Equation 3.5, task clarification is mapping of  $Ne$  into  $FuCo$ . The mapping operation is largely dependent on designers' experience and hence bioinspired design expects.

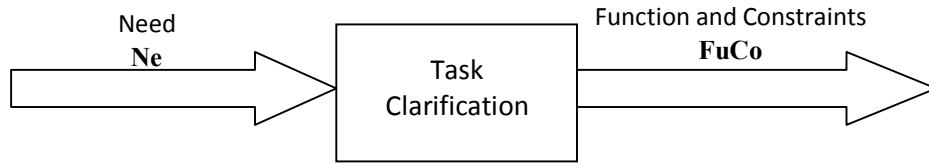


Figure 3.7 Representation of the task clarification as transformer

$$FuCo = \emptyset (Ne) \quad (3.5)$$

The set of  $FuCo$  has two elements as given in Equation 3.6; one of them is a set of sub-functions ( $Fu$ ) shown in Equation 3.7 where  $Fu_i$  is the sub-function in functional decomposition. Each sub-function is described by the corresponding locomotion type ( $Loc_i$ ) and its kinematic data ( $Kin_i$ ). Therefore,  $Fu_i$  is represented as in Equation 3.8.

$$FuCo = \{Fu, Co\} \quad (3.6)$$

$$Fu = \{Fu_1, Fu_2, \dots, Fu_k\} \quad (3.7)$$

$$Fu_i = \{Loc_i, Kin_i\} \quad (3.8)$$

The other element of FuCo is the set of constraints (Co) as defined in Equation 3.9 where each element is a set of described as follows;

*SBS*: Set of Species for a **B**iological **S**ystem which is initially known for a SB-BICD.

*Mor*: Set of expected **M**orphology for the biorobot which covers information an appearance (App), size (Siz), weight (Weh), height (Heh), and the number of legs (NuL) as given in Equation 3.10.

*Spe*: Set of Specified Features of the Biorobot including information about material, energy, signal, modularity of the biorobot.

*OpE*: Set of **O**perational **E**nvironment such as temperature (Tep) and surface (Sur) represented in Equation 3.11.

*Cos*: is the **C**ost.

*Sce*: is the **S**chedule of the design.

*Cos* and *Sce* are used if the requirements list includes related information.

$$Co = \{SBS, Mor, Spe, OpE, Cos, Sce\} \quad (3.9)$$

$$Mor = \{App, Siz, Weh, Heh, NuL\} \quad (3.10)$$

$$OpE = \{Tep, Sur\} \quad (3.11)$$

### 3.3.2 Biological System Selection

In this step, two cases are considered depending on SB-BICD and PB-BICD. In the first case, the starting point of the design is solution-based (SB) and it is assumed that species of a biological system (SBS) are known. In the second case, SBS is unknown and the approach is problem-based (PB).

The aim of this step is to clarify the breed(s) of the biological system(s) required for inspiration to design of a biorobot. Thus, in the PB-BICD, firstly, the *SBS* should be selected from various alternatives of the species. This selection is based on *Fu* and *Co*. After that, alternatives for breeds of biological systems (BrBS) for the selected species should be generated according to function(s) for both SB-BICD and PB-BICD and collected as a set ( $I_2$ ). This can be performed by using various sources,

such as literature or existing databases. Some of the databases were tabulated in Table 2.3 in Chapter 2. The generated alternatives should be eliminated and a breed(s) of a biological system(s) are selected considering constraints ( $Co$ ).

Two main activities are considered in this step. The first activity is “generating” alternatives of the  $SBS$  and the second one is “selecting” a convenient  $BrBS$  for each function. These activities are illustrated in Figure 3.8. It should be noted that more feasible biological systems or  $BrBS$  is selected when  $Fu$  and  $Co$  are well-defined and well-organized.

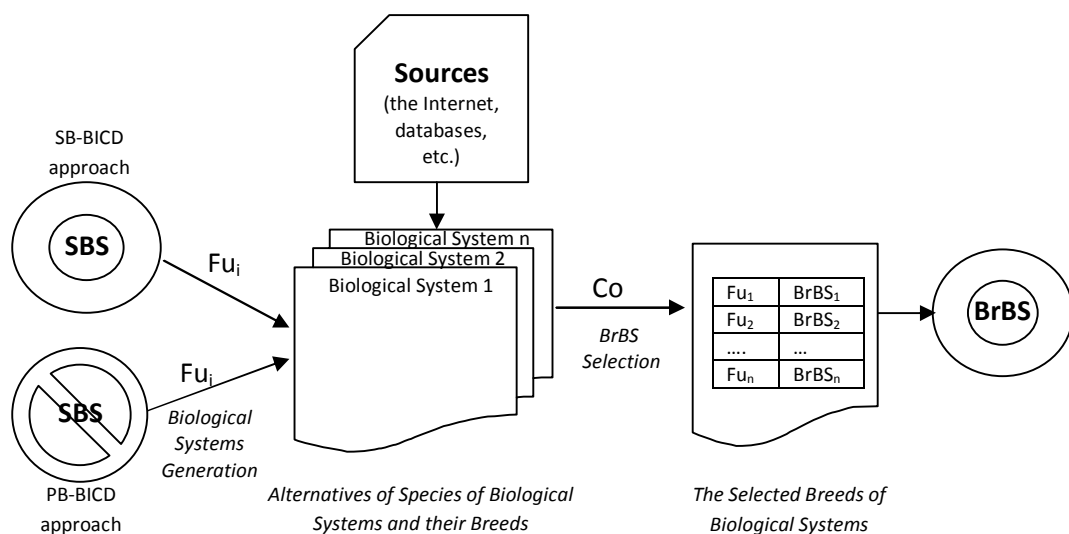


Figure 3.8 The steps of biological system selection

Three different situations of biological systems selection arise:

1. A biological system inspires the design of a biorobot which performs a function. This situation is observed especially in the SB-BICD. For instance, the climbing motion of an American cockroach may be used to design a climbing biorobot.
2. A biological system may be selected for inspiration to perform multiple sub-functions of a biorobot. For example, climbing and walking are our expected functions and one of the constraints is the number of legs which is given as six (6). A cockroach may be selected for functions of walking and climbing regarding the  $Co$ .
3. Several biological systems may be selected for each sub-function of a biorobot. This approach supports creative and innovative design. In that case,

the output of the BICD process is the hybrid biorobots. For example, climbing and walking are our expected functions without the considering the number of legs as a constraint. The functions of a cockroach climbing and a dog walking may be integrated in a biorobot.

### 3.3.3 Biological System Analysis

The literature shows that two important points should be well-defined for a systematic BICD process. One of them arises “Biological System Analysis” stage and the second is observed in bioinspired transformation step, explained in Section 3.3.4.

**a. Required Knowledge to Represent Biological Systems:** Sartori and Chakrabarti [2010] state that “Even well-known biological solution can trigger innovative solutions in engineering if the knowledge is available at the right time and in the right form, a common language with which the functionality of both biological and engineered systems could be expressed” It is known that analysis of biological systems is used to collect “correct” knowledge which should be transformed from biological to engineering domain. Thus, an important question arises; “What is the required knowledge which represents biological systems?” In order to answer this question, two approaches are used in this study [Konez Eroğlu et al., 2011\_a]. Firstly, the definition of “biorobot” is investigated so that the requirements of biorobots inspired from biological systems are determined. Secondly, existing case studies on biorobots are studied to collect properties of biological systems which are used for inspiration.

i. Biorobot Definition: The suggested BICD process is constructed to develop design concepts for biorobots. Thus, before discussing the analysis step for biological systems, it is necessary to define biorobots and required knowledge. There are several definitions for biorobots in the literature [Webb and Consi, 2001; Bar-Cohen, 2006\_a; Meyer and Guillot, 2008] and they can be merged in the following definition.

Biorobots, biologically inspired (bioinspired) robots or biomimetic robots, emulate the functions and performance of biological systems, look like the inspiration model and behave similarly to the original model.

This definition is represented in a semantic network as shown in Figure 3.9. It should be noted that the purpose here is to use a semantic network as a well-known technique for the representation of relationships between concepts [Sowa, 2006], rather than to search for the most efficient representation scheme.

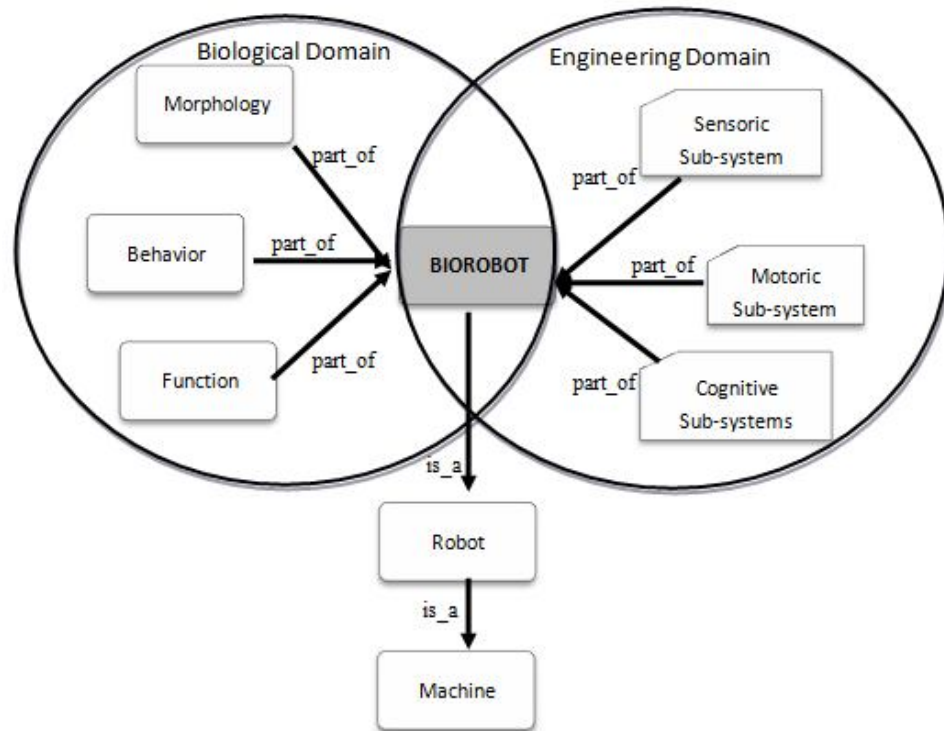


Figure 3.9 A semantic network representation of a biorobot

Figure 3.9 gives representation of a biorobot as a machine, which includes sensoric, motoric, and cognitive sub-systems in the engineering domain. In addition, the biorobot has morphology, behavior and function features which should be obtained from biological systems.

ii. Existing Case Studies on Biorobots: In order to find “correct” knowledge of biological systems, the related literature on bioinspired robot case studies has been reviewed. The major consideration in the literature is to determine those aspects of the unknown biology that should be included in the robot model [Webb and Consi, 2001]. There are various ideas about the required knowledge and some of them are tabulated in Table 3.2.

Table 3.2 Examples of different knowledge on biological systems collected from different case studies

Reference	BS Knowledge about	Study on
[Wiebe, 2009]	Ecology Morphology Anatomy Physiology	Dynamic building
[Eduardo et al., 2008]	Biomechanical architecture Sensory cognitive system	Human hand
[Hu et al., 2009]	Function and performance (kinematic modeling)	Fish fins
[Laksanacharoen et al., 2000]	Morphology Locomotion behavior	Walking and jumping of a cricket
[Wang et al., 2008]	Morphology Jumping movement (kinematic data)	Jumping of a frog
[Menon et al., 2009]	Morphology Mechanical structure	Campanifer sensilla of insects
[Sitorus et al., 2009]	Locomotion system (Function) Anatomy Morphology	Fish fins locomotion

Table 3.2 shows that the knowledge used for transformation from biological domain to engineering domain can be investigated under the following category terms;

- Anatomy
- Behavior
- Biomechanical architecture
- Ecology
- Function
- Mechanical structure
- Morphology
- Physiology
- Sensory cognitive system

These terms are defined in Appendix A as they are used in the relevant literature [Marieb and Hoehn, 2006; Barnard, 2004; Erden et al., 2008; Robertson et al., 2004; Eicher and Simmons, 2007; Wilson, 2008; Pahl et al., 2007; Söylemez, 2009; Matro, 2009; Webb and Consi, 2001]. A semantic network representation of these terms is based using their definitions, given in Figure 3.10.

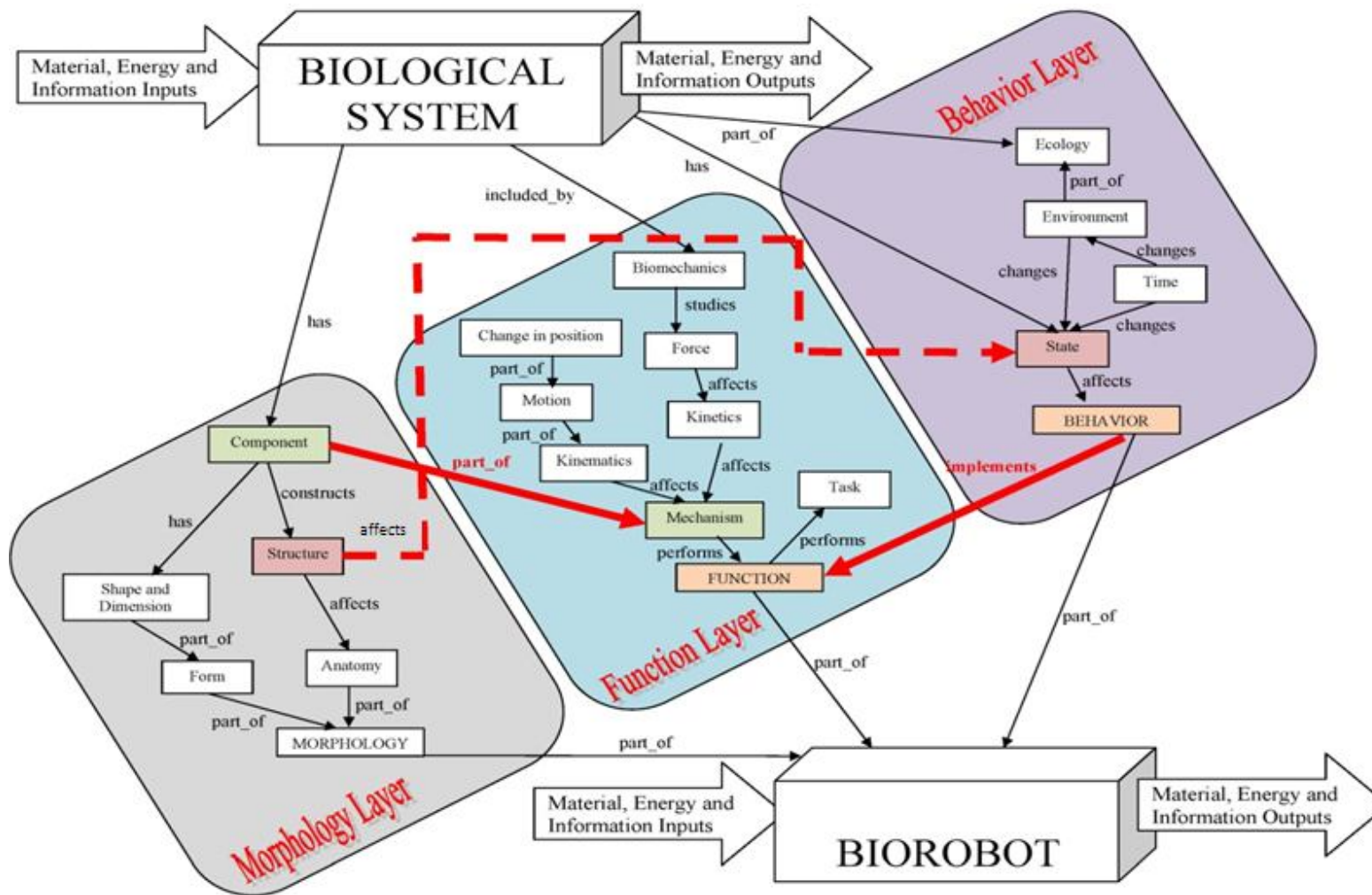


Figure 3.10 A semantic network representation of concepts used in case studies on biorobots

This network, displayed in Figure 3.10, shows that motion and forces are related with the function which performs a task. Form and structure are parts of morphology, which includes the anatomy of a biological system. Behavior of a biological system affected by changes in the environment can implement different functions [Kitamura et al., 2006]. Therefore, “function”, “morphology”, and “behavior” features can be used to represent a biological system to design a biorobot which includes energy, material, and information inputs and outputs as a system. The morphological information includes dimensions (length, shape, etc.), weight and body structure details (the number of links, joint details, etc). The forms of biological systems perform vital functions economically [French, 1996]. The functional decomposition component supplies a function structure, mathematical models for desired kinematic data, and performance (dynamic data) of the biological systems. The behavioral model gives information about how the biological system achieves the desired function.

According to Figure 3.10, knowledge of “function”, “morphology”, and “behavior” can be used to represent a biological system to design a biorobot which includes energy, material, and information flow as a system. As Gero’s model (FBS) [Gero and Kannengiesser, 2002], structures are discussed for knowledge representation. However, it is believed that the structure information is not enough to represent biological systems. Information about dimensions, shapes and structure connections should also be discussed. Therefore, morphology, function, and behavior are preferred in the BICD procedure.

**b. Biological System Analysis:** This step includes three activities which are preparing, collecting and organizing. These activities are schematically represented in Figure 3.11. In the first activity, the designer prepares analysis information and/or an experimental set-up with respect to  $Fu$  and  $Co$ . If it is necessary to design and construct a set-up, it is completed in the activity. In “collecting”, the designer collects data and information about the  $BrBS$  or  $BS$ . The collection is satisfied for  $Fu$  with respect to  $Co$ . Two data collection methods are discussed to obtain the required knowledge about a biological system. The first one is the content method in which data is collected by consulting biologists and using literature survey. The collected data is considered as a set and in the thesis study; this set is represented with  $I_3$ . The second one is the observation which is an empirical method involving observation

and measurements. A combination of these methods is preferred to collect more accurate data about the selected biological system. The third activity, “organizing” is used to analyze the collected data and organize them into the categories of morphology, function, and behavior of the biological system.

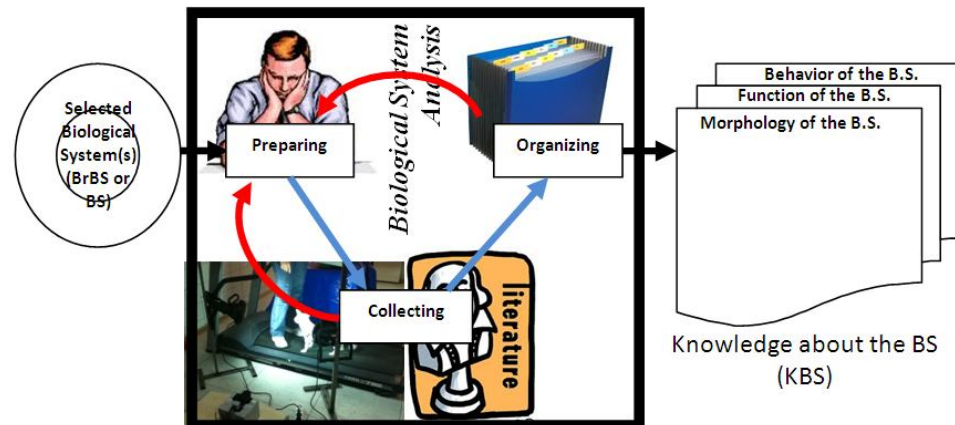


Figure 3.11 An illustration of the biological system analysis step

The biological system analysis is an iterative process as represented in Figure 3.11. Once data collection is completed, the designer may return to the preparing activity, if s/he decides that the experimental set-up or documents should be constructed or reviewed again. Similarly, if the designer decides after the organizing activity, the collected data is not sufficient to represent the biological system, s/he may return to “preparing” activity.

Output of this stage is the set of knowledge about the selected biological system (KBS) given in Equation 3.12, where *MorBS*, *FuBS*, and *BeBS* represent to **M**orphology of the **B**iological System, **F**unction of the **B**iological System, and **B**ehavior of the **B**iological System.

$$KBS = \{MorBS, FuBS, BeBS\} \quad (3.12)$$

Morphology is a science dealing with the form and structure of biological systems without a consideration of function. Since this research is limited to jointed-leg locomotion, **M**orphology of **B**iological System (MorBS) includes:

- *DiBS*- the **D**imensions of the **B**iological **S**ystem,
- *WeBS*- the **W**eight of the **B**iological **S**ystem,
- *NuL*- the **N**umber of **L**egs,
- *PaL*- the **P**aired **L**egs according to anatomic structure,
- *LoL*- the **L**imbs of each paired **L**egs,
- *FoLb*- the **F**orms of **L**imbs,
- *JoL*- the **J**oint of each paired **L**egs,
- *ToJo*- the **T**ypes of **J**oints, and
- *SoM*- the **S**tructure of **M**uscles (if required).

Therefore, *MorBS* is represented as a set in Equation 3.13.

$$\text{MorBS} = \{\text{DiBS}, \text{WeBS}, \text{NuL}, \text{PaL}, \text{LoL}, \text{FoLb}, \text{JoL}, \text{ToJo}, \text{SoM}\} \quad (3.13)$$

Expected function(s) is exposed in the task clarification step. In the biological system analysis step, the function(s) should be detailed by answering the question “What does the biological system do?” Behavior, which can implement different functions, is a sequential change of states over time with respect to a change in the internal state of the body or in the environment. In the dissertation, visual behaviors of biological systems are considered. In order to understand behavior, the question of “How does the biological system do selected function(s)?” should be answered.

### 3.3.4 Bioinspired Transformation

Studies on the BICD show that two steps should be well-defined for a systematic BICD. The first one is the biological system analysis step which was discussed in Section 3.3.2. The second is the “Bioinspired Transformation” stage, in which the question of “How the knowledge about the biological system is transformed into the engineering domain?” arises. The transformation is achieved with four activities: matching, separating, modeling and synchronizing. In “matching”, forms and structures are matched with the existing engineering forms and structures. For example, the tibia of a dog may be matched with a cylindrical prism or a rectangular prism and its knee may be modeled with a pin support.

“Separating” is to clarify the locomotion cycle of a biorobot. If the biorobot repeats a cycle, it performs the function with a stable state and exhibits behavior of the biological system. Then, in “modeling”, the collected data of the biological system for a locomotion cycle is shifted or linearized. Biological systems have flexible structures. Because of this flexibility, when they complete a locomotion cycle with values of joint angles different from the initial values, biological systems can satisfy stability anyway. This situation is different for the biorobots because they must complete the cycle with the same values and repeat the cycle with the same values for stabilization. Thus, the angle values are shifted according to the initial value to remove the differences between the initial and final values.

The last activity of the transformation is the “synchronizing” step. In “synchronizing”, information about the function and behavior is considered in 3D. All legs are considered for the expected function.

The output of this stage can be represented as a set of Knowledge about Biorobot (KBR). The *KBR* is given in Equation 3.14 where *MorBR* is the Morphology of the biorobot and represented as a set in Equation 3.15. *NuL*, *PaL*, *LoL*, *FoLb*, *JoL* and *ToJo* are considered in the engineering domain. *MorBR* includes some assumptions. For example, although for a grasshopper *NuL* of *MorBS* is 6, *NuL* of *MorBR* may be selected as 4, because studies show that grasshoppers can jump by using only rear legs: the other two leg pairs are only used for elevating the body and they can be modeled as a pair. Thus, 2 leg pairs and 4 legs can be used for the biorobot of grasshopper-like jump locomotion. *FuBR* and *BeBR* represent the function and behavior of biorobots. *FuBR* include expected function, kinematic data and joint angles during the locomotion cycle. *BeBR* covers leg combinations during the cycle. Another output of the bioinspired transformation step is set of information about biological systems ( $I_4$ ) that can be used in the engineering domain. In future, if sufficient numbers of biological systems are analyzed and transformed into the engineering domain by using the  $I_4$  a database for the design of biorobots will be provided.

$$KBR = \{MorBR, FuBR, BeBR\} \quad (3.14)$$

$$MorBR = \{NuL, PaL, LoL, FoLb, JoL, ToJo\} \quad (3.15)$$

### 3.3.5 Engineering Structures Generalization

By using creative methods (such as brainstorming) and the sources (such as the Internet or databases), engineering structures can be generated based on  $Fu$  and  $Co$  and arranged in a set ( $I_5$ ). Then, appropriate alternatives can be organized with a morphological matrix. Thus, in this stage of the BICD, main activities are generalizing and tabulating in which some of the alternatives are eliminated with respect to the  $Co$ .

Organized engineering structures are shown in Table 3.3 where  $M$ ,  $A$  and  $C$  represent materials, actuators and controllers, respectively. As seen in the table, two different controllers may be preferred for the function and the behavior of the biorobot.

Table 3.3 A representative sketch for a Morphological Matrix

	Type of engineering structure	Alternative Engineering Structures						
		$M_1$	$M_2$	$M_3$	...			$M_n$
MorBR	Material	$M_1$	$M_2$	$M_3$	...			$M_n$
FuBR	Actuator	$A_1$	$A_2$	$A_3$		....		$A_n$
	Controller	$C_{11}$	$C_{12}$	$C_{13}$			....	$C_{1n}$
BeBR	Controller	$C_{21}$	$C_{22}$	$C_{23}$			...	$C_{2n}$

### 3.3.6 Engineering Structures Selection

The last step of the BICD process is the selection of engineering structures. At the end of this step, the concept of the expected biorobot will be obtained. To select the most appropriate concept, three further activities should be performed. These activities are combining, rating and selecting. In the “combining”, the concept variants are generated with the combinations of engineering structures by using the Morphological Matrix which should have already been tabulated in the engineering structures generalization stage. Then, in “rating”, each concept variant is rated with weights. In the literature, there are various methods to determine weighting such as:

- Objective Tree [Pahl et al., 2007]
- Pugh’s concept selection method [Eggert, 2005],
- Weighted-rating method [Eggert, 2005], and
- Mechatronic Design Quatients (MDQ) [Benbahani, 2007].

After this, a concept of the biorobot should be selected in the activity of “selecting” Thus, the selected alternative becomes the output of the BICD process and the concept of the biorobot.

### **3.4 CHAPTER SUMMARY**

A detailed explanation of the suggested BICD process has been given in Chapter 3. The philosophy of the BICD is introduced in Section 3.1. The BICD approach is discussed in Section 3.2. The BICD process is developed based on the analogical reasoning in which source and target domains are biology and engineering. Although the starting domain is biology for knowledge transformation, the design process begins with a need in engineering domain independent from SB or PB and finishes with the concept design of a biorobot. Six steps are considered from the need to the concept of the biorobot. These steps are detailed in Section 3.3. The next chapter, Chapter 4, presents the model of the BICD process.

## CHAPTER 4

### MODEL OF THE BICD PROCESS

This thesis proposes a BICD Methodology which is based on the systematic representation of the process described in Chapter 3. Classic Discrete Event System Specification (DEVS) coupled model is selected systematic representation so as to develop a BICD process model which is explained in Chapter 4 as depicted in Figure 4.1.

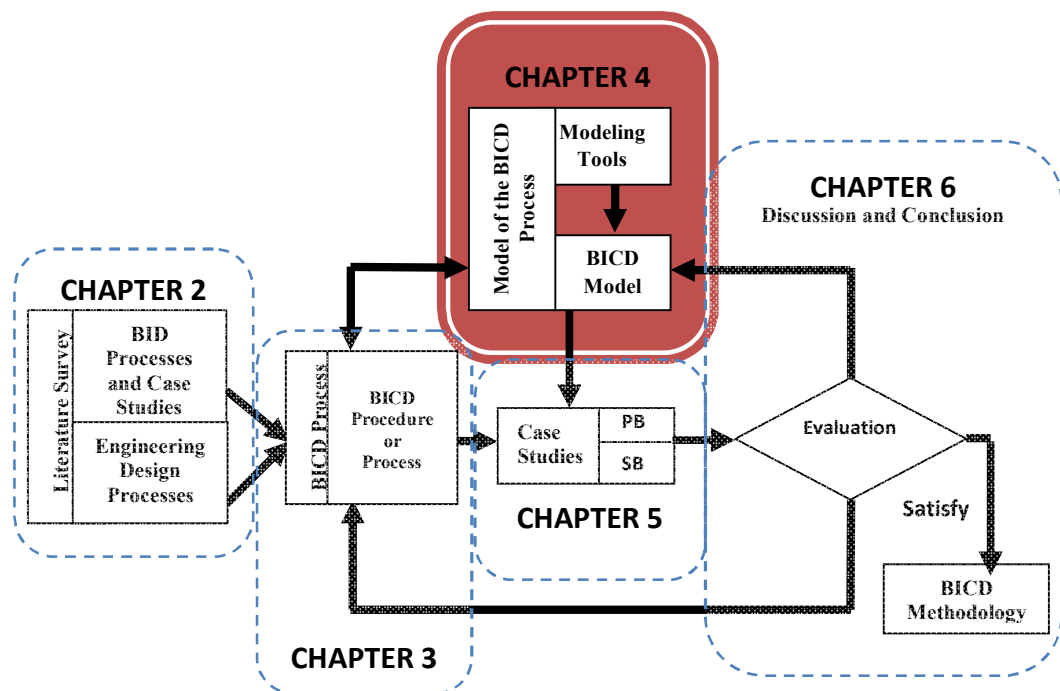


Figure 4.1 Chapter 4 and organization of the dissertation

The data flow diagram of the BICD process which represents the inputs and outputs of each step is given in Section 4.1. Section 4.2 discusses the reasons for the

selection of the classic DEVS coupled model this thesis. Section 4.3 explains the DEVS model and Section 4.4 introduces the BICD process model based on the DEVS representations. The classic DEVS coupled model of the BICD process is given in Section 4.4.1. In Section 4.4.2 classic DEVS atomic model of each state of the process is represented. A general view of the developed model is discussed in Section 4.5. Symbols used within the chapter are tabulated in the List of Abbreviations.

#### 4.1 DATA FLOW DIAGRAM OF THE BICD PROCESS

In order to develop the BICD process model, a systematic representation of the BICD stages with their inputs and outputs is required. Long [2002] compares several graphical representations based on a behavior characteristics spectrum which is given in Figure 4.2.

Data Flow Diagram (DFD) is selected to represent the BICD process since it does not require any control mechanism and it allows much more data representation in the same time. The DFD of the BICD process is shown in Figure 4.3. The sets of these inputs and outputs were described in Section 3.3.

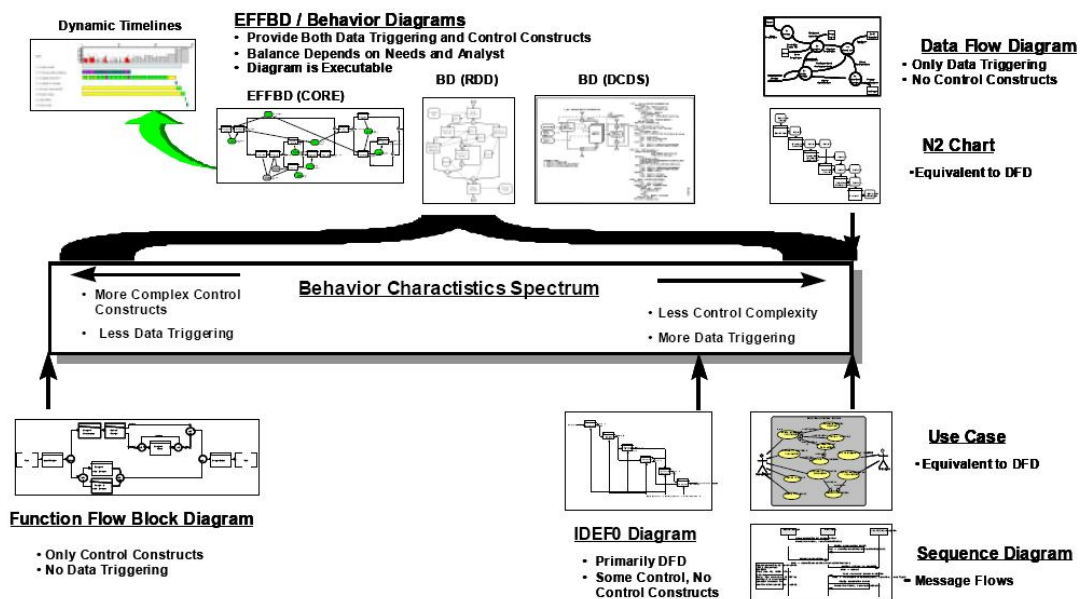


Figure 4.2 Relationships of all graphical representations [Long, 2002]

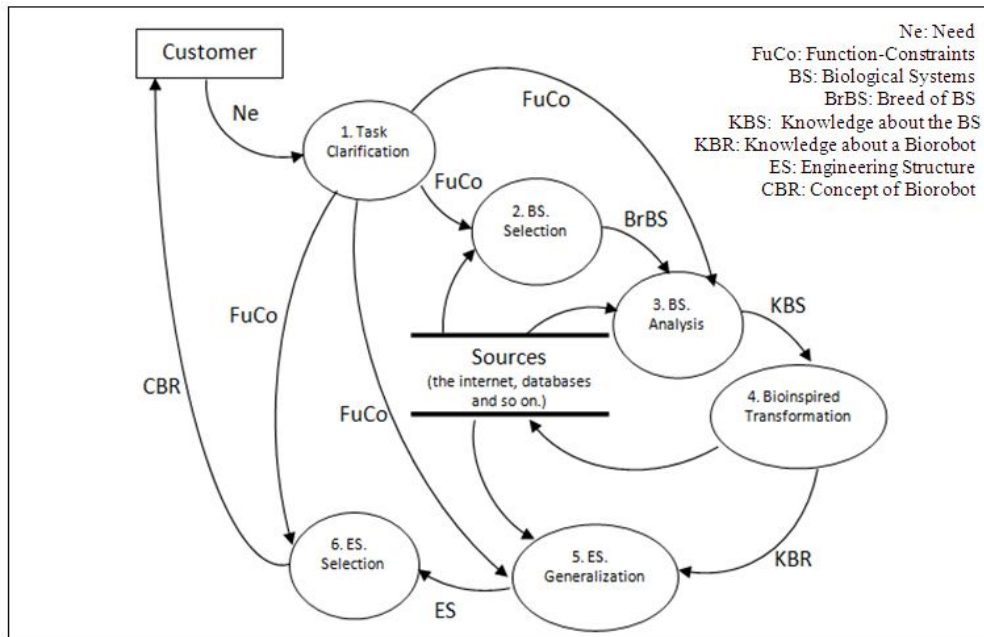


Figure 4.3 The Data Flow Diagram (DFD) of the BICD Process

#### 4.2 MODEL SELECTION

Table 4.1 compares characteristics of the BICD process and model alternatives which are discussed in Chapter 2. It is apparent from Table 4.1 that declarative modeling is applicable to the BICD process if the process is represented as composed of “states” A state is defined by Fishwick [1995] as a system description for an interval of time. Similarly, an event is a point in time that designates a change in state. According to Fishwick, a state is represented by participial phrases for a verb, such as “emptying” and “boiling” while an event is represented with its related state name and a verb, such as “end emptying” and “start boiling” States of the BICD process for declarative modeling are identified based on Fishwick’s definition and they are tabulated in Table 4.2 with corresponding input(s) and output(s).

Table 4.1 Comparison of the model alternatives with characteristics of the process

Characteristics of the Process	Model Alternatives				
	Conceptual	Declarative	Functional	Constraint	Spatial
Qualitative data	√	√	√		√
Inputs and Outputs	√	√	√	√	√
State/Event-based		√	√	√	
Discrete States		√			
No equation/physical law		√			

Table 4.2 States of the BICD process with inputs and outputs

<b>States</b>	<b>Input(s)</b>	<b>Output(s)</b>
Task clarifying	Need (Ne)	FuCo
Biological system selecting	FuCo Information (I <sub>2</sub> )	BrBS
Biological system analyzing	FuCo BrBS Information (I <sub>3</sub> )	KBS
Bioinspired transforming	KBS	KBR Information (I <sub>4</sub> )
Engineering structure generalizing	FuCo KBR Information (I <sub>5</sub> )	ES
Engineering structure selecting	FuCo ES	CBR

DEVS (Discrete Event System Specification) is an extension of finite state automata (FSA) [Fishwick, 1995] and a type of the declarative model. DEVS was firstly introduced to the public by Dr. Bernard P. Zeigler and it is defined as a modular and hierarchical formalism for modeling and analyzing discrete event systems whose dynamic behavior is governed by event occurrence [Zeigler, 1989]. DEVS formalism has an ability to effectively represent a system and its behavior.

In this thesis study, in order to develop a BICD methodology, DEVS is selected for the BICD process model because of its systematic and mathematical model structure which is appropriate for defining a process. The BICD process is considered as a system because the process transforms customer needs (the input) to a concept design of biorobot (the output) with use of interdependent process steps that are defined as states within the developed the BICD process model. These states do not change throughout the process and remain unchanged for different concept designs of biorobots. On the other hand, events which are inputs and outputs of each state may vary dependent on the customer needs. Hence, the developed BICD process model considered as an event-based DEVS model.

Two main types of DEVS are discussed in the literature. These are classic DEVS and parallel DEVS. In the classic DEVS, only one state is processed in an external event. In contrast, multiple states are processed at the same time in the parallel DEVS. The BICD process includes sequential states that are, when a state is started to be

processed the previous one has been completed. Hence, the classic DEVS is chosen to model the BICD process.

The literature survey studies on DEVS show that two main types of DEVS are considered. These are “Atomic DEVS” and “Coupled DEVS” Atomic one is a basic formulation and it is used to model the system behavior. If the system includes multiple states, it can be modeled with the coupled DEVS. In the coupled DEVS, the system behavior is also defined with different atomic DEVS formulations at the same time. It means that, when the coupled DEVS is applied, the atomic DEVS should be automatically included in the model.

### 4.3 CLASSIC DEVS COUPLED MODEL

The classic DEVS coupled model is defined as an eighth-tuple by Zeigler [Zeigler et al., 2000]. The modified form of the model is given in Equation 4.1.

$$N = (X, Y, D, \{M_d \mid d \in D\}, EIC, EOC, IC, \text{Select}) \quad (4.1)$$

In Equation 4.1,

- X is a set of inputs to the system,
- Y is the set of outputs of the system,
- D is the set of the state names,
- $M_d$  is the atomic DEVS model of each state,  $d \in D$ ,
- EIC is an external input coupling connecting external inputs to state inputs which is given in Equation 4.2,
- EOC is an external output coupling connecting state outputs to external outputs which is given in Equation 4.3,
- IC is an internal coupling connecting state outputs to state inputs which is given in Equation 4.4 and
- Select:  $2^D - \{ \} \rightarrow D$ , the tie-breaking function. It is used to define how to select the event from the set of simultaneous events.

$$EIC = \{((N, i_N), (d, i_d)) \mid i_N \in X, d \in D, i_d \in X_d\} \quad (4.2)$$

$$EOC = \{((d, o_d), (N, o_N)) \mid o_N \in Y, d \in D, o_d \in Y_d\} \quad (4.3)$$

$$IC = \{((a, o_a), (b, i_b)) \mid a, b \in D, o_a \in Y_a, i_b \in X_b\} \quad (4.4)$$

In Equation 4.2 and 4.3,  $N$  represents the system;  $i$  and  $o$  represent the input and the output, respectively.  $X_d$  is the input set of a state,  $d$  and  $Y_d$  is the output set of  $d$ . In Equation 4.4,  $a$  and  $b$  are any two states of the system.

In Equation 4.1,  $M_d$  represents the classic DEVS atomic model of each state,  $d$ .  $M_d$  for the BICD process model is defined in Equation 4.5 which is the modified form of the original representation given in [Zeigler et al., 2000].

$$M_d = (X_d, Y_d, S, \delta_{ext}, \delta_{int}, \lambda, ta) \quad (4.5)$$

In Equation 4.5,

- $X_d$  is the set of inputs of a state,  $d$ ,
- $Y_d$  is the set of outputs of a state,  $d$ ,
- $S$  is a set of sub-states covered by  $d$ ,
- $\delta_{ext} : Q \times X_d \rightarrow S$  is the external transition function,  
where  $Q = \{(s, e) \mid s \in S, 0 \leq e \leq ta(s)\}$  is the total state set, and  $e$  is the time elapsed since last transition,
- $\delta_{int} : S \rightarrow S$  is the internal transition function,
- $\lambda : S \rightarrow Y_d$  is the output function,
- $ta : S \rightarrow \mathbb{R}^+_{0, \infty}$  is the expiration time of the states.

Zeigler and his colleagues [Zeigler and Sarjoughian, 1998; Zeigler et al., 2000; Zeigler and Sarjoughian, 2005] interpret the state ( $S$ ), external and internal transition functions ( $\delta_{ext}$  and  $\delta_{int}$ ), output function ( $\lambda$ ) and expiration time ( $ta(s)$ ). These are illustrated in Figure 4.4. It is assumed that the system is in some specific state ( $S$ ). If there is no external event, the system remains in state  $S$  for time  $ta(s)$ . When the elapsed time is  $e = ta(s)$ , the system changes into the state  $s' = \delta_{int}(s)$  and the state output ( $\lambda(s)$ ) arises. If an external event  $x \in X$  occurs before the expiration time (when  $e < ta(s)$ ), the system changes to state  $s' = \delta_{ext}(s, e, x)$ .

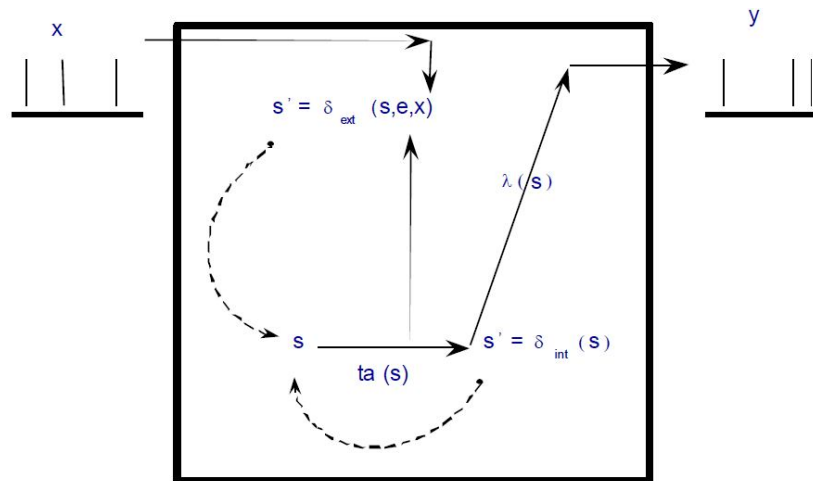


Figure 4.4 DEVS in action [Zeigler and Sarjoughian, 1998; Zeigler et al., 2000; Zeigler and Sarjoughian, 2005]

It is discussed that the states are easily illustrated with DEVS trajectories [Zeigler and Sarjoughian, 1998; Zeigler et al., 2000; Zeigler and Sarjoughian, 2005]. An example of the DEVS trajectory given in [Zeigler et al., 2000] is displayed in Figure 4.5. As shown in the figure, the input trajectory is a series of events occurring at different times such as  $t_0$  and  $t_2$ .  $t_1$  is the time of internal event. The state trajectory, illustrated with a step-like series, changes when external/ internal events occur in the system. The elapsed time trajectory, illustrated with a sawtooth pattern, represents the elapsed times. The output trajectory depicts the output events.

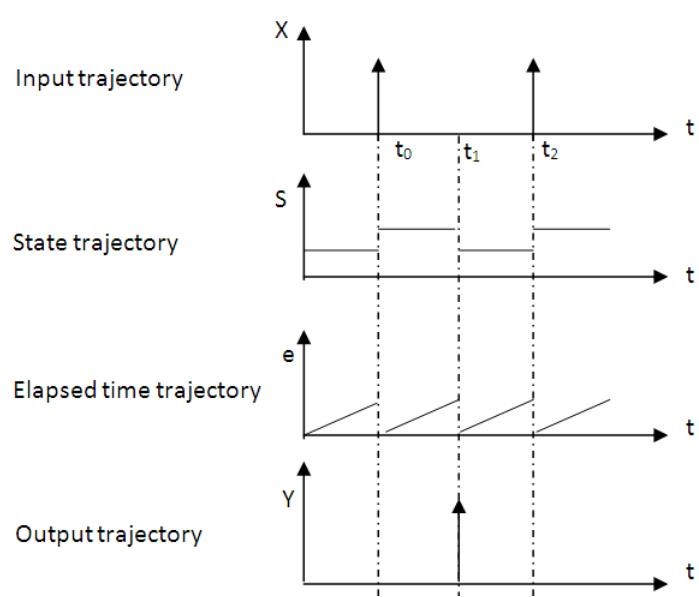


Figure 4.5 An example of the DEVS Trajectory [Zeigler et al., 2000]

#### 4.4 DEVS MODEL OF THE BICD PROCESS

The classic DEVS coupled model of the BICD process is given in Figure 4.6 which represents states of the BICD process as well as inputs and outputs of each state. In the figure,  $S_1, S_2, S_3, S_4, S_5$  and  $S_6$  represent states of the BICD process;  $I_2, I_3, I_4$  and  $I_5$  are the information inputs/outputs of these states. The numbers used in the designations relates the information inputs/outputs ( $I_i$ s) to their related states ( $S_i$ s). Since the input of the  $S_1$  is “need” (Ne),  $I_1$  input is not used in the model. Customer and information sources are considered in an environment which is outside of the system boundary of the BICD process. The other abbreviations were explained in Figure 4.3.

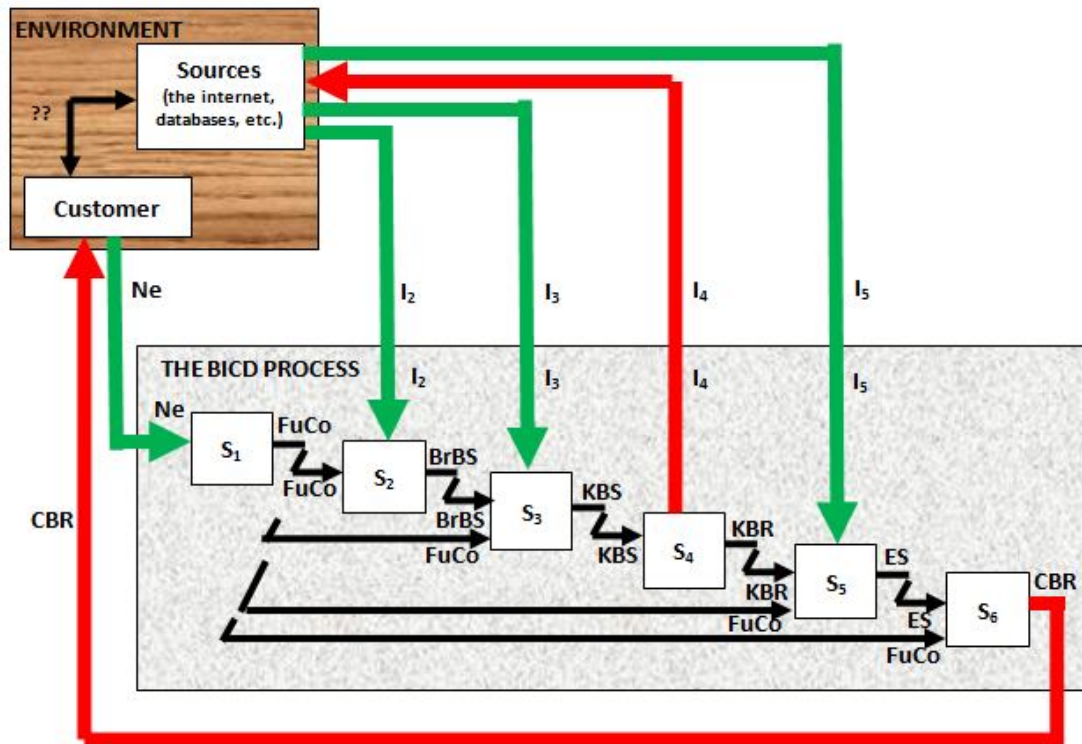


Figure 4.6 BICD process classic DEVS coupled model

##### 4.4.1 Classic DEVS Coupled Model for the BICD Process

The coupled DEVS model specification for the BICD process is given in Equation 4.6.

$$N_{\text{BICD}} = (X, Y, D, \{M_d \mid d \in D\}, \text{EIC}, \text{EOC}, \text{IC}, \text{Select}) \quad (4.6)$$

Elements of  $N_{\text{BICD}}$  are explained below.

- i.  $X$  is the set of inputs to the system (BICD process) and it is given in Equation 4.7.

$$X = \{(Ne, k_1), (I_2, k_2), (I_3, k_3), (I_5, k_5) \mid k_1, k_2, k_3, k_5 \in K\} \quad (4.7)$$

$Ne$  is a set of needs which is collected from the customer's sentences.  $I_2$  represents a set of information about species and breeds of biological systems which perform the required function.  $I_3$  represents information about the selected (breed of the) biological system (BS).  $I_5$  is information about engineering structures which are used in concept variants of the biorobot. Thus, system inputs are  $Ne$ ,  $I_2$ ,  $I_3$  and  $I_5$  and they are represented with a set of keywords. Hence,  $K$  is defined as a set of keywords. Members of  $K$  are keywords that represent customer needs ( $k_1$ ) and/or keywords that represent information about the biological and engineering domain obtained from various sources ( $k_2$ ,  $k_3$  and  $k_5$ ), such as the Internet and available databases.

- ii.  $Y$  is the set of outputs of the BICD process and it is given in Equation 4.8.

$$Y = \{(I_4, k_4), (CBR, k_6) \mid k_4, k_6 \in K\} \quad (4.8)$$

$I_4$  is a set of information about the biological system which has been selected and analyzed in the process. This information is used in engineering domain.  $CBR$  is the "concept of a biorobot" which is the expected output of the BICD process. Similar to the  $Ne$ ,  $I_4$  and  $CBR$  are represented with a set of keywords ( $k_4$ ,  $k_6 \in K$ ).

- iii.  $D$  is the set of state names of the system.  $D$  is given in Equation 4.9.

$$\begin{aligned} D &= \{S_1, S_2, S_3, S_4, S_5, S_6\} \\ &= \{\text{"Task Clarifying"}, \text{"Biological System Selecting"}, \text{"Biological System Analyzing"}, \text{"Bioinspired Transforming"}, \text{"Engineering Structure Generalizing"}, \text{"Engineering Structure Selecting"}\} \end{aligned} \quad (4.9)$$

The states were defined as the steps of the BICD process in Section 3.3.

- iv.  $M_d$  represents the classic DEVS atomic model of the BICD process states as represented in Equation 4.10. Details of the  $M_d$  are given in Section 4.3.2.

$$M_d = \{M_{d1}, M_{d2}, M_{d3}, M_{d4}, M_{d5}, M_{d6}\} \quad (4.10)$$

- v.  $EIC$  is the set of external input coupling connecting external inputs to state inputs which is given in Equation 4.11. As displayed in Figure 4.6, customer and the sources are considered outside of the system.  $Ne$  is the output of the customer while  $I_2, I_3$  and  $I_5$  are outputs of the sources.

$$EIC = \{((N_{BICD}, Ne), (S_1, Ne)), ((N_{BICD}, I_2), (S_2, I_2)), \\ ((N_{BICD}, I_3), (S_3, I_3)), ((N_{BICD}, I_5), (S_5, I_5))\} \quad (4.11)$$

- vi.  $EOC$  is an external output coupling connecting state outputs to external outputs which is given in Equation 4.12.

$$EOC = \{((S_6, CBR), (N_{BICD}, CBR)), ((S_4, I_4), (N_{BICD}, I_4))\} \quad (4.12)$$

- vii.  $IC$  is an internal coupling connecting state outputs to state inputs which is given in Equation 4.13.

$$IC = \{((S_1, FuCo), (S_2, FuCo)), ((S_2, BrBS), (S_3, BrBS)), ((S_3, KBS), \\ (S_4, KBS)), ((S_4, KBR), (S_5, KBR)), ((S_5, ES), (S_6, ES))\} \quad (4.13)$$

- viii.  $Select$  is the tie-breaking function used to clarify the application order of the states. In this study, the order of states is considered respectively as  $S_1, S_2, S_3, S_4, S_5, S_6$ .

In Section 4.3.1 classic DEVS coupled model of the BICD process is introduced. In this model,  $M_d$  (Equation 4.10) represents a set of the atomic models for the BICD states, which are explained in Section 4.3.2.

#### 4.4.2 Classic DEVS Atomic Model for Each State of the BICD Process

##### i. Task Clarifying ( $S_1$ )

In the “task clarifying state” of the BICD process, the customer needs ( $Ne$ ) are tabulated in a requirements list and needs are classified into functions ( $Fu$ ) and constraints ( $Co$ ). The details of the “task clarifying” step were given in Section 3.3.1.

The DEVS trajectories of  $S_1$  are illustrated in Figure 4.7. Classic DEVS atomic model of  $S_1$  is given in Equation 4.14. The input of the state is  $Ne$  and outputs are  $Fu$  and  $Co$  as represented in Equation 4.15 and Equation 4.16, respectively.

$$M_{d1} = (X_{d1}, Y_{d1}, S_{S1}, \delta_{ext1}, \delta_{int1}, \lambda_1, ta_1) \quad (4.14)$$

$$X_{d1} = \{(Ne, k_1) \mid k_1 \in K\} \quad (4.15)$$

$$Y_{d1} = \{(Fu, k_7), (Co, k_8) \mid k_7, k_8 \in K\} \quad (4.16)$$

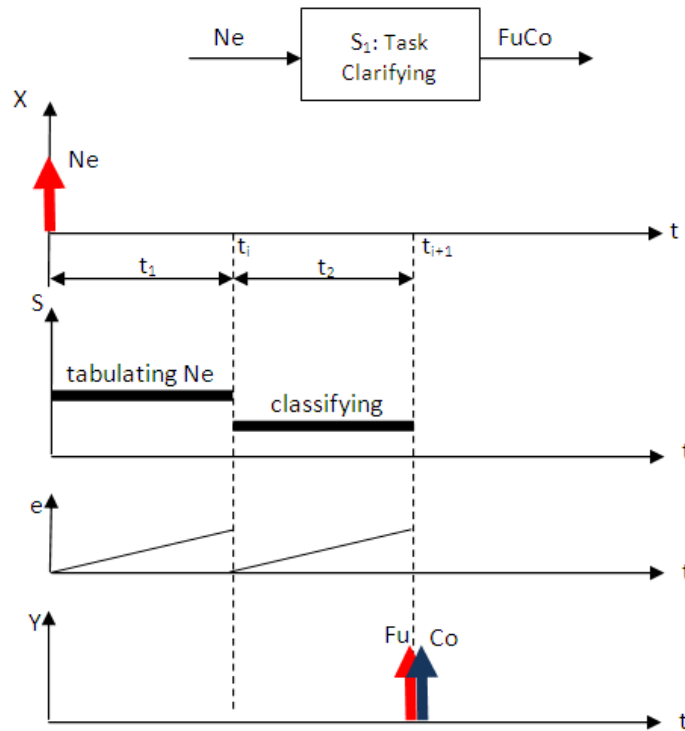


Figure 4.7 DEVS Trajectories for  $S_1$  (Task Clarifying)

State trajectory in Figure 4.7 shows two sub-states of  $S_1$ ; these are “tabulating Ne” and “classifying” as given in Equation 4.17. In the “tabulating Ne”, keywords (collected from the customer’s sentences) are written in the requirements list. The “classifying” sub-state is used to identify the functions (Fu) and constraints (Co) using the requirements list.

$$S_{S1} = \{\text{“tabulating Ne”}, \text{“classifying”}\} \quad (4.17)$$

As given in Equation 4.18, during  $S_1$ , there is no external event. When the input event of “!complete tabulating” is considered, sub-state of “tabulating Ne” is changed into the sub-state of “classifying” at  $t_i$  (Equation 4.19) and the requirements list is set forth. At the end of the “classifying”, there is no an internal transition, shown in Equation 4.20. The output of the state (Fu and Co) arises only at the end of the “classifying” (Equation 4.21 and Equation 4.22).

$$\delta_{ext1} (\text{sub-state}_1, \sigma_1, e, x) = \emptyset \quad (4.18)$$

$$\delta_{int1} (\text{“tabulating Ne”}) = (!\text{complete tabulating}, \text{“classifying”}) \quad (4.19)$$

$$\delta_{int1} (\text{“classifying”}) = \emptyset \quad (4.20)$$

$$\lambda_1 (\text{“tabulating Ne”}, t_i) = \emptyset \quad (4.21)$$

$$\lambda_1 (\text{“classifying”}, t_{i+1}) = \{\text{Fu}, \text{Co}\} \quad (4.22)$$

Equation 4.23 represents the sub-states’ time ( $ta_1$ ) which are equal to the expiration time ( $\sigma_1$ ). Each time is shown in Equation 4.24 and Equation 4.25.

$$ta_1 (\text{sub-state}_1, \sigma_1) = \sigma_1 \quad (4.23)$$

$$\sigma_1 (\text{“tabulating Ne”}) = t_i \quad (4.24)$$

$$\sigma_1 (\text{“classifying”}) = t_{i+1} \quad (4.25)$$

## ii. Biological System Selecting ( $S_2$ )

The “biological system selecting ( $S_2$ )” state is modeled based on the explanation given in Section 3.3.2. The classic DEVS atomic model of the  $S_2$  is given in Equation 4.26 and its DEVS trajectories are represented in Figure 4.8.

Figure 4.8 shows the  $Fu$ ,  $Co$  and  $I_2$  are inputs of  $S_2$  (Equation 4.27).  $I_2$  is the set of information about the species and the breeds of biological systems.  $I_2$  is collected from the available sources, such as the literature, the databases and the Internet. The output of the  $S_2$  is a breed(s) of a biological system(s) (BrBS) which is given in Equation 4.28.

Two sub-states of  $S_2$  are “generating” and “selecting BS” as given in Equation 4.29. In “generating” sub-state, species and breeds of a biological system(s) are determined based on  $Fu$  by using  $I_2$ . “Selecting BS” is used to make a selection a breed(s) of the biological system(s) with respect to  $Co$ .

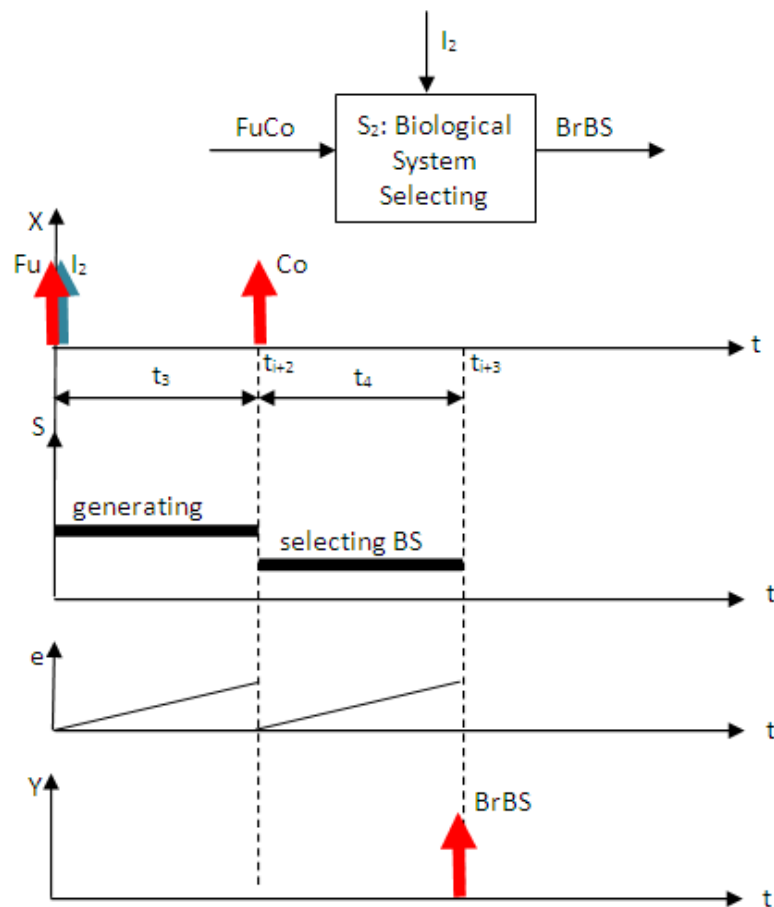


Figure 4.8 DEVS Trajectories for  $S_2$  (Biological System Selecting)

$$M_{d2} = (X_{d2}, Y_{d2}, S_{S2}, \delta_{ext2}, \delta_{int2}, \lambda_2, ta_2) \quad (4.26)$$

$$X_{d2} = \{(Fu, k_7), (Co, k_8), (I_2, k_2) \mid k_2, k_7, k_8 \in K\} \quad (4.27)$$

$$Y_{d2} = \{(BrBS, k_9) \mid k_9 \in K\} \quad (4.28)$$

$$S_{S2} = \{\text{"generating"}, \text{"selecting BS"}\} \quad (4.29)$$

When the input *Co* is added at the end of the “generating” (Equation 4.30) and time of “generating” ( $t_{i+2}$ ) is expired by the designer with the input event “!complete generating” (Equation 4.32), the sub-state of “generating” is changed into “selecting BS” sub-state. At the end of the “selecting BS”, neither an external transition function (Equation 4.31) nor an internal transition function (Equation 4.33) is considered.

$$\delta_{ext2} (\text{"generating"}, t_{i+2}, t_3, Co) = \text{"selecting BS"} \quad (4.30)$$

$$\delta_{ext2} (\text{"selecting BS"}, t_{i+3}, t_4, x) = \emptyset \quad (4.31)$$

$$\delta_{int2} (\text{"generating"}) = (!complete generating, \text{"selecting BS"}) \quad (4.32)$$

$$\delta_{int2} (\text{"selecting BS"}) = \emptyset \quad (4.33)$$

As given Equation 4.34, there is no output after the “generating” The output of the  $S_2$  (BrBS) exists after the “selecting BS” (Equation 4.35). Equations 4.36 to 4.38 represent the expiration times of sub-states.

$$\lambda_2 (\text{"generating"}, t_{i+2}) = \emptyset \quad (4.34)$$

$$\lambda_2 (\text{"selecting BS"}, t_{i+3}) = \{BrBS\} \quad (4.35)$$

$$ta_2 (\text{sub-state } 2, \sigma_2) = \sigma_2 \quad (4.36)$$

$$\sigma_2 (\text{"generating"}) = t_{i+2} \quad (4.37)$$

$$\sigma_2 (\text{"selecting BS"}) = t_{i+3} \quad (4.38)$$

## ii. Biological System Analyzing ( $S_3$ )

In Section 3.3.3, the biological system analyzing is explained. The DEVS trajectories and block box illustration of state ( $S_3$ ) is depicted in Figure 4.9. Classic DEVS atomic model of  $S_3$  is given in Equation 4.39. As shown in Figure 4.9, the inputs of the state are  $Fu$ ,  $Co$ ,  $BrBS$  and  $I_3$  while its output is knowledge about the selected biological system(s) ( $KBS$ ). The sets of inputs ( $X_{d3}$ ) and output ( $Y_{d3}$ ) are represented in Equation 4.40 and Equation 4.41.

$$M_{d3} = (X_{d3}, Y_{d3}, S_{S3}, \delta_{ext3}, \delta_{int3}, \lambda_3, ta_3) \quad (4.39)$$

$$X_{d3} = \{(Fu, k_7), (Co, k_8), (BrBS, k_9), (I_3, k_3) \mid k_3, k_7, k_8, k_9 \in K\} \quad (4.40)$$

$$Y_{d3} = \{(KBS, k_{10}) \mid k_{10} \in K\} \quad (4.41)$$

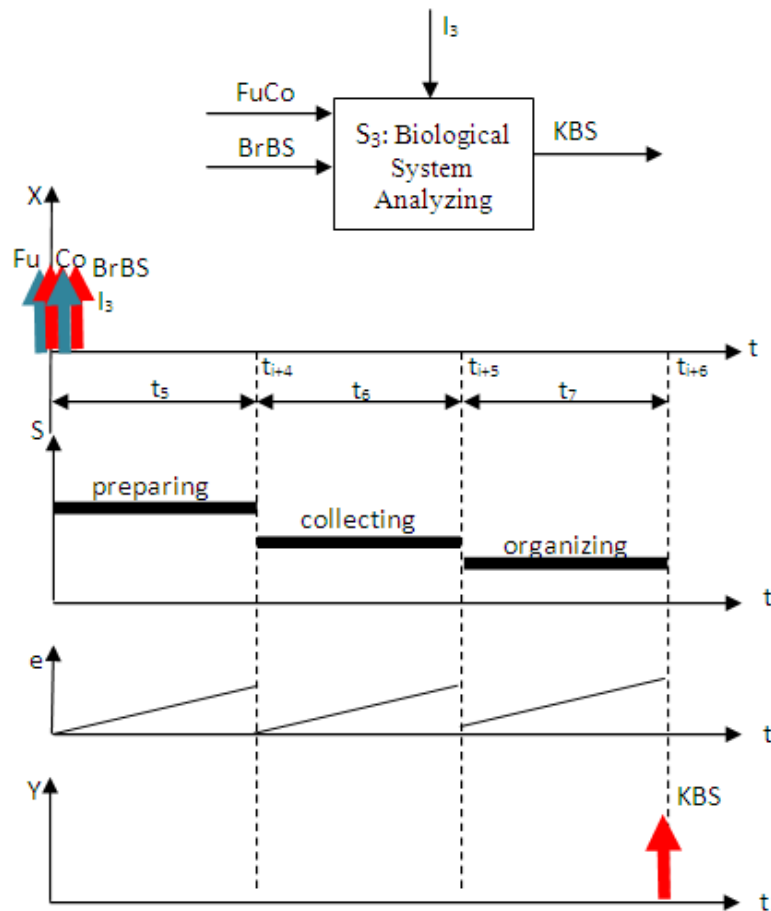


Figure 4.9 DEVS Trajectories for  $S_3$  (Biological System Analyzing)

As stated before, the sub-states of  $S_3$  are “preparing”, “collecting” and “organizing” represented in Equation 4.42. There is no external transition between sub-states as shown in Equation 4.43.

$$S_{S_3} = \{\text{“preparing”}, \text{“collecting”}, \text{“organizing”}\} \quad (4.42)$$

$$\delta_{\text{ext}3}(\text{sub-state}_3, \sigma_3, e, x) = \emptyset \quad (4.43)$$

$S_3$  starts with an initial state “preparing”, in which the designer works for analysis of information and/or development of an experimental set-up based on  $Fu$  and  $Co$ . If it is necessary to design and construct a set-up, it is completed in this sub-state. The “collecting” sub-state models data collection process about the selected biological system(s). As discussed in Section 3.3.2, two methods are considered in the BICD process for biological system analysis. These are content analysis and observation. If content analysis method is applied, literature survey is required. Such a survey uses  $I_3$  and it is based on  $Fu$  and  $Co$ . An experimental set-up should be designed and constructed in the observation method. In the “organizing” state, the collected knowledge is classified under the titles of “morphology (MorBS)”, “function (FuBS)” and “behavior (BeBS)” The output of  $S_3$  is the knowledge about the biological system (KBS) including these clusters. The sub-states and transitions between them are shown in Figure 4.10 as a DEVS diagram.

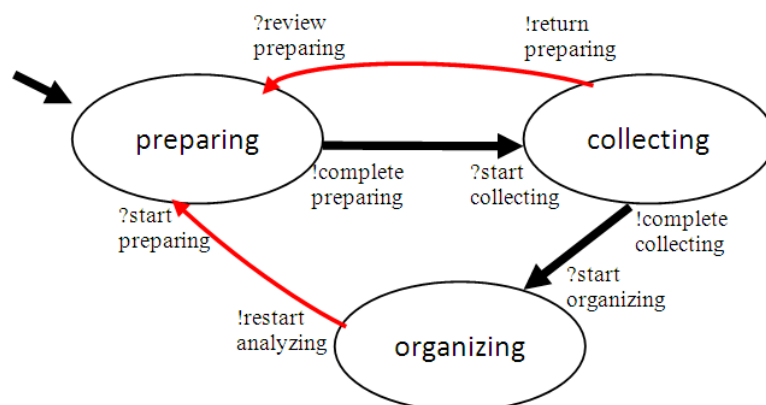


Figure 4.10 An illustration of the transitions between sub-states for  $S_3$

As shown in Figure 4.10, the process is started with “preparing” The output event of “preparing” (!complete preparing) is transmitted to input event of “collecting” (?start collecting) when the sub-state is transformed from “preparing” to “collecting”, given in Equation 4.44. When the designer is at the “collecting”, following two alternative ways are obtained.

1. If the designer is not satisfied from the collected data, s/he may return to the “preparing” from the “collecting” sub-state and s/he reviews the analysis method and may updates the method. Hence, the output event of “collecting” (!return preparing) is transmitted to input event of “preparing” (?review preparing) which is given in Equation 4.45.
2. If the designer believes that collected data about the biological system is sufficient, s/he may continue the process and goes to the last sub-state “organizing” Thus, the second output event of “collecting” (!complete collecting) is transmitted to input event of “organizing” (?start organizing) which is given in Equation 4.46.

In the “organizing”, a similar situation is observed. Two ways of the “organizing” are summarized below.

1. If the designer does not satisfy from the knowledge about the biological system clustering into morphology, function and behavior, s/he can return the initial sub-state “preparing” Hence, the output event of “organizing” (!restart analyzing) is transmitted to input event of “preparing” (?start preparing) which is given in Equation 4.47.
2. If the designer believes that the required knowledge about the biological system was sufficiently collected and it can be used in engineering domain, s/he can go to the next state  $S_4$ . There are not an internal transition and a transition function (Equation 4.48). The output of the  $S_3$  is the *KBS* (Equations 4.49 to 4.51).

In  $S_3$ , the main assumption is that expiration time required to change sub-states depends on the designer as given in Equations 4.52 to 4.55.

$$\delta_{\text{int}3} (\text{“preparing”}) = (!\text{complete preparing, “collecting”}) \quad (4.44)$$

$$\delta_{\text{int}3} (\text{“collecting”}) = (!\text{return preparing, “preparing”}) \quad (4.45)$$

$$\delta_{\text{int}3} (\text{“collecting”}) = (!\text{complete collecting, “organizing”}) \quad (4.46)$$

$$\delta_{\text{int}3} (\text{“organizing”}) = (!\text{restart analyzing, “preparing”}) \quad (4.47)$$

$$\delta_{\text{int}3} (\text{“organizing”}) = \emptyset \quad (4.48)$$

$$\lambda_3 (\text{“preparing”}, t_{i+4}) = \emptyset \quad (4.49)$$

$$\lambda_3 (\text{“collecting”}, t_{i+5}) = \emptyset \quad (4.50)$$

$$\lambda_3 (\text{“organizing”}, t_{i+6}) = \{\text{KBS}\} \quad (4.51)$$

$$\text{ta}_3 (\text{sub-state}_3, \sigma_3) = \sigma_3 \quad (4.52)$$

$$\sigma_3 (\text{“preparing”}) = t_{i+4} \quad (4.53)$$

$$\sigma_3 (\text{“collecting”}) = t_{i+5} \quad (4.54)$$

$$\sigma_3 (\text{“organizing”}) = t_{i+6} \quad (4.55)$$

### iii. Bioinspired Transforming ( $S_4$ )

Bioinspired transformation is described in Section 3.3.4. Classic DEVS atomic model of  $S_4$  is given in Equation 4.56. A block representation and DEVS trajectories of the state of bioinspired transforming state ( $S_4$ ) are given in Figure 4.11. The figure shows that the input of  $S_4$  is  $KBS$  (Equation 4.57), and its outputs are  $I_4$  and  $KBR$  (Equation 4.58).  $I_4$  is the set of information about BS which will be used in the engineering domain and  $KBR$  represents the set of knowledge about the biorobot (BR) including its morphology (MorBR), function (FuBR) and behavior (BeBR).

$$M_{d4} = (X_{d4}, Y_{d4}, S_{S4}, \delta_{\text{ext}4}, \delta_{\text{int}4}, \lambda_4, \text{ta}_4) \quad (4.56)$$

$$X_{d4} = \{(\text{KBS}, k_{10}) \mid k_{10} \in K\} \quad (4.57)$$

$$Y_{d4} = \{(I_4, k_4), (\text{KBR}, k_{11}) \mid k_4, k_{11} \in K\} \quad (4.58)$$

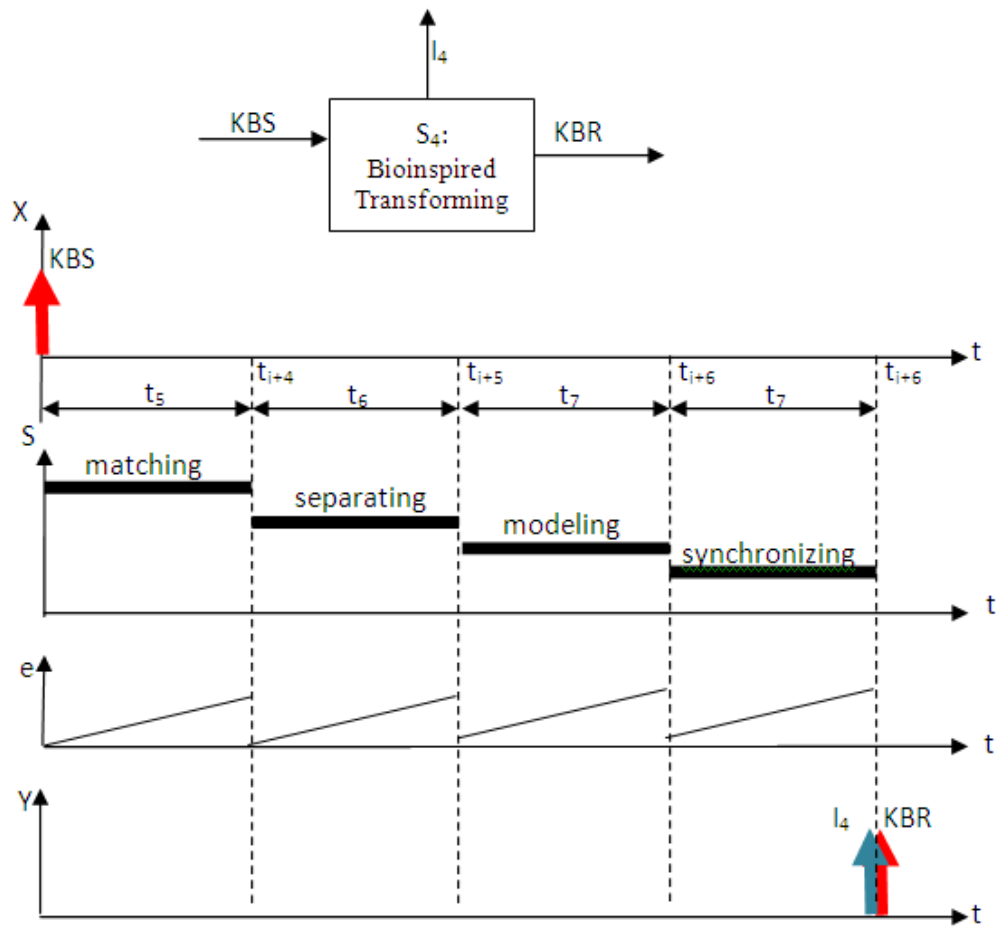


Figure 4.11 DEVS Trajectories for  $S_4$  (Bioinspired Transforming)

$S_4$  has four sub-states; “matching”, “separating”, “modeling” and “synchronizing” (Equation 4.59) and they are defined in Section 3.3.4. In general, in the “matching” sub-state, forms and structures of BS are matched with known engineering forms and structures. While the “matching” provides  $MorBR$ , the other three sub-states are considered in  $FuBR$  and  $BeBR$ . Since the scope of this research is focused on the locomotion behavior of biological systems, in the “separating” sub-state, a locomotion cycle of a  $BR$  is achieved. The “modeling” sub-state is used to clarify linearized/switched data of angles. This type of data is required for stabilization of a  $BR$ , when it exhibits the expected behavior. In the “synchronizing” sub-state, two-dimensional (2D) data obtained in “biological system analysis” state is transferred to three-dimensional (3D) data for a  $BR$ . It is assumed that, no iteration is performed in  $S_4$  because it is difficult to realize errors at this state. The errors can be obtained after producing the prototype. However, in the thesis, conceptual design is considered, so

manufacturing part is not discussed and it is assumed that  $S_4$  has a sequential and straight forward structure. This structure is represented in Figure 4.12.

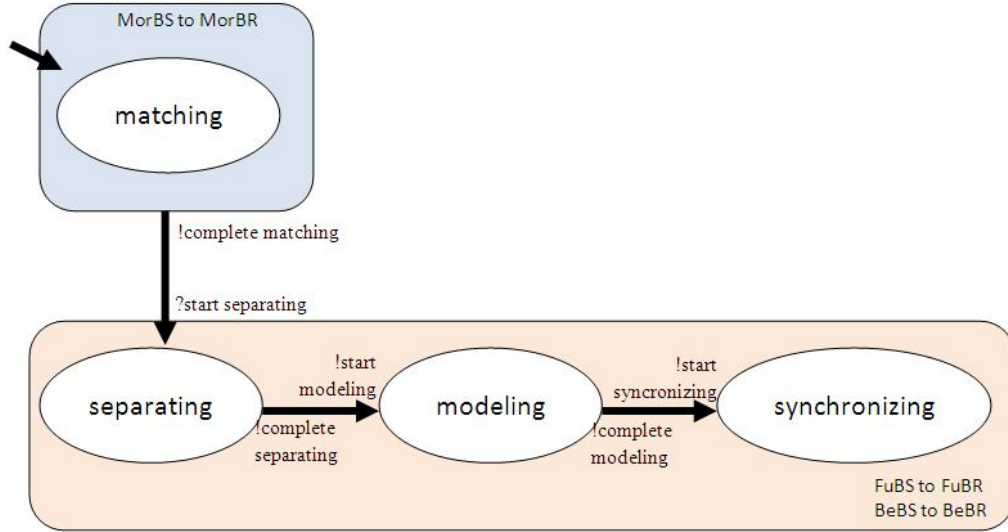


Figure 4.12 Illustration of the sequential and straight forward structure of  $S_4$

$$S_{S_4} = \{\text{"matching"}, \text{"separating"}, \text{"modeling"}, \text{"synchronizing"}\} \quad (4.59)$$

In  $S_4$ , there is no external transition function as shown in Equation 4.60 in which *sub-state*<sub>4</sub> and  $\sigma_4$  represent the state variables. Internal transition functions based on input/output events of the sub-states (illustrated in Figure 4.12) are given in the Equations 4.61 to 4.64. When the “synchronizing” is completed, the output of the state, *KBR* arises (Equations 4.65 to 4.68).

$$\delta_{\text{ext}4}(\text{sub-state}_4, \sigma_4, e, x) = \emptyset \quad (4.60)$$

$$\delta_{\text{int}4}(\text{"matching"}) = (!\text{complete matching}, \text{"separating"}) \quad (4.61)$$

$$\delta_{\text{int}4}(\text{"seperating"}) = (!\text{complete seperating}, \text{"modeling"}) \quad (4.62)$$

$$\delta_{\text{int}4}(\text{"modeling"}) = (!\text{complete modeling}, \text{"synchronizing"}) \quad (4.63)$$

$$\delta_{\text{int}4}(\text{"synchronizing"}) = \emptyset \quad (4.64)$$

$$\lambda_4(\text{"matching"}, t_{i+7}) = \emptyset \quad (4.65)$$

$$\lambda_4(\text{"seperating"}, t_{i+8}) = \emptyset \quad (4.66)$$

$$\lambda_4 (\text{“modeling”}, t_{i+9}) = \emptyset \quad (4.67)$$

$$\lambda_4 (\text{“synchronizing”}, t_{i+10}) = \{KBR\} \quad (4.68)$$

Similar to the other states, the expiration times of each sub-state is decided by the designer and shown in Equations 4.69 to 4.73.

$$ta_4 (\text{sub-state}_4, \sigma_4) = \sigma_4 \quad (4.69)$$

$$\sigma_4 (\text{“matching”}) = t_{i+7} \quad (4.70)$$

$$\sigma_4 (\text{“seperating”}) = t_{i+8} \quad (4.71)$$

$$\sigma_4 (\text{“modeling”}) = t_{i+9} \quad (4.72)$$

$$\sigma_4 (\text{“synchronizing”}) = t_{i+10} \quad (4.73)$$

#### iv. Engineering Structure Generalizing ( $S_5$ )

“Engineering Structure Generalizing” state is explained in Section 3.3.5. In this section, classic DEVS atomic model of  $S_5$  is developed and given in Equation 4.74. The inputs of  $S_5$  are  $Fu$ ,  $Co$ ,  $KBR$  and  $I_5$  are given in Equation 4.75.  $I_5$  is the information collected from various sources about engineering structures, such as the Internet and databases. The output of this state is engineering structures (ES), given in Equation 4.76.

$$M_{d5} = (X_{d5}, Y_{d5}, S_{S5}, \delta_{ext5}, \delta_{int5}, \lambda_5, ta_5) \quad (4.74)$$

$$X_{d5} = \{(Fu, k_7), (Co, k_8), (I_5, k_5), (KBR, k_{12}) \mid k_7, k_8, k_5, k_{12} \in K\} \quad (4.75)$$

$$Y_{d5} = \{(ES, k_{13}) \mid k_{13} \in K\} \quad (4.76)$$

As it has been stated in Section 3.3.5,  $S_5$  has two sub-states; “generalizing” and “tabulating engineering structures (ES)” as given in Equation 4.77. These sub-states are shown in Figure 4.13.

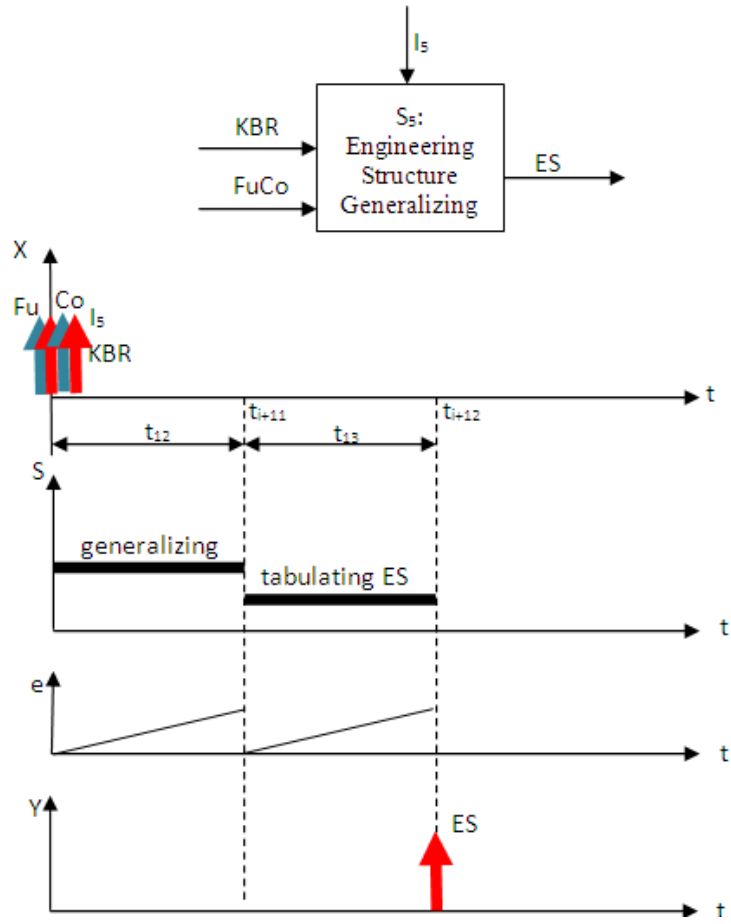


Figure 4.13 DEVS Trajectories for  $S_5$  (Engineering Structure Generalizing)

$$S_{S5} = \{\text{"generalizing"}, \text{"tabulating ES"}\} \quad (4.77)$$

In the “generalizing”, alternatives of engineering structures are generated based on  $I_5$  and these structure alternatives are classified and tabulated in a Morphological Matrix in the “tabulating ES” based on  $KBR$ ,  $Fu$  and  $Co$ . There is no an external transition between the sub-states (Equation 4.78), only internal transitions are obtained (Equation 4.79 and Equation 4.80).

$$\delta_{ext5}(\text{sub-states}_5, \sigma_5, e, x) = \emptyset \quad (4.78)$$

$$\delta_{int5}(\text{"generalizing"}) = (!\text{complete generalizing}, \text{"tabulating ES"}) \quad (4.79)$$

$$\delta_{int5}(\text{"tabulating ES"}) = \emptyset \quad (4.80)$$

After “tabulating ES” sub-state, ES arises as given in Equation 4.81 and Equation 4.82. Equations 4.83 to 4.85 represent the expiration times of each sub-state.

$$\lambda_5 (\text{“generalizing”}, t_{i+11}) = \emptyset \quad (4.81)$$

$$\lambda_5 (\text{“tabulating ES”}, t_{i+12}) = \{ES\} \quad (4.82)$$

$$ta_5 (\text{sub-state}_5, \sigma_5) = \sigma_5 \quad (4.83)$$

$$\sigma_5 (\text{“generalizing”}) = t_{i+11} \quad (4.84)$$

$$\sigma_5 (\text{“tabulating ES”}) = t_{i+12} \quad (4.85)$$

#### v. Engineering Structure Selecting ( $S_6$ )

The last state of the DEVS process is “engineering structure selecting” for which details are given in Section 3.3.6. Block representation and DEVS trajectories of  $S_6$  are displayed in Figure 4.14. Classic DEVS atomic model of  $S_6$  is given in Equation 4.86. Inputs of  $S_6$  are  $Fu$ ,  $Co$  and  $ES$  are given in Equation 4.87 while Equation 4.88 gives the output of the state,  $CBR$ .  $CBR$  represents the concept of the biorobot which is the expected output of the BICD process.

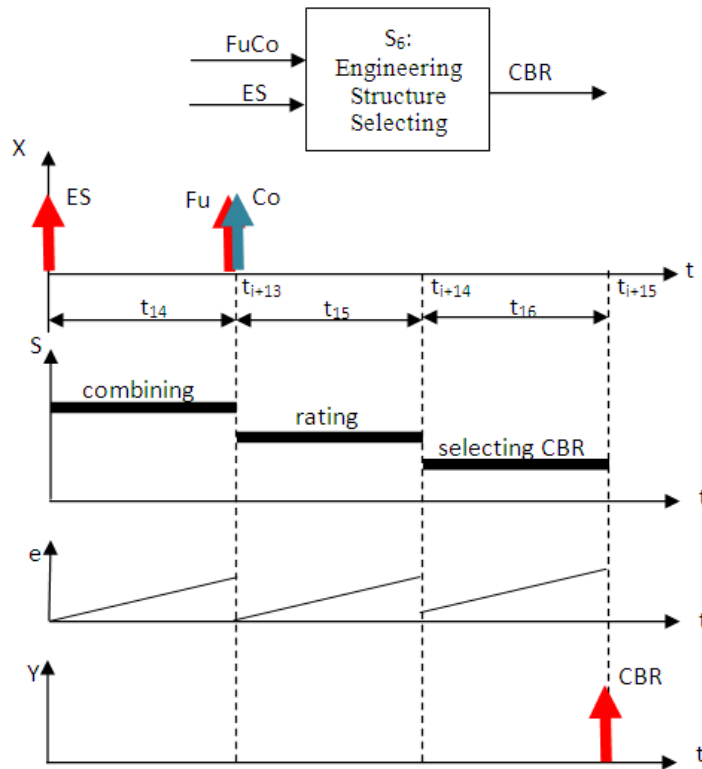


Figure 4.14 DEVS Trajectories for  $S_6$  (Engineering Structure Selecting)

$$M_{d6} = (X_{d6}, Y_{d6}, S_{S6}, \delta_{ext6}, \delta_{int6}, \lambda_6, ta_6) \quad (4.86)$$

$$X_{d6} = \{(Fu, k_7), (Co, k_8), (ES, k_{13}) \mid k_{13}, k_7, k_8 \in K\} \quad (4.87)$$

$$Y_{d6} = \{(CBR, k_6) \mid k_6 \in K\} \quad (4.88)$$

As illustrated in Figure 4.14, sub-states of  $S_6$  are “combining”, “rating” and “selecting” which are given in Equation 4.89. The “combining” state represents a state in which concept variants of the biorobot are generated. When  $Fu$  and  $Co$  are inserted into the  $S_4$  (Equation 4.90) and the designer decides to complete the “combining” at  $t_{i+13}$  (Equation 4.93), “rating” sub-state is started. Equation 4.91 and Equation 4.92 represent that there is no state change between the other sub-states. In the “rating” state, the conceptual design alternatives are ranked based on weights. Weights are calculated based on  $Fu$  and  $Co$  using methods which are examined in Section 3.3.3. When the designer completes “rating”, s/he starts to “selecting CBR”. This internal transition is shown in Equation 4.94. Equation 4.95 represents that there is no state transition for “selecting CBR” sub-state in which a concept of biorobot (CBR) is selected as shown in Equation 4.98. The other sub-states do not give a direct output (Equation 4.96 and Equation 4.97). Equations 4.99 to 4.102 give the expiration times of the sub-states.

$$S_{S6} = \{\text{“combining”}, \text{“rating”}, \text{“selecting CBR”}\} \quad (4.89)$$

$$\delta_{ext6} (\text{“combining”}, t_{i+13}, t_{14}, \{Fu, Co\}) = \text{“rating”} \quad (4.90)$$

$$\delta_{ext6} (\text{“rating”}, t_{i+14}, t_{15}, x) = \emptyset \quad (4.91)$$

$$\delta_{ext6} (\text{“selecting CBR”}, t_{i+15}, t_{16}, x) = \emptyset \quad (4.92)$$

$$\delta_{int6} (\text{“combining”}) = (!\text{complete combining}, \text{“rating”}) \quad (4.93)$$

$$\delta_{int6} (\text{“rating”}) = (!\text{complete rating}, \text{“selecting CBR”}) \quad (4.94)$$

$$\delta_{int6} (\text{“selecting CBR”}) = \emptyset \quad (4.95)$$

$$\lambda_6 (\text{“combining”}, t_{i+13}) = \emptyset \quad (4.96)$$

$$\lambda_6 (\text{“rating”}, t_{i+14}) = \emptyset \quad (4.97)$$

$$\lambda_6 (\text{“selecting CBR”}, t_{i+15}) = \{CBR\} \quad (4.98)$$

$$ta_6 (\text{sub-state}_6, \sigma_6) = \sigma_6 \quad (4.99)$$

$$\sigma_6 (\text{“combining”}) = t_{i+13} \quad (4.100)$$

$$\sigma_6 (\text{“rating”}) = t_{i+14} \quad (4.101)$$

$$\sigma_6 (\text{“selecting CBR”}) = t_{i+15} \quad (4.102)$$

#### **4.5 GENERAL VIEW OF THE CLASSIC DEVS COUPLED MODEL OF THE BICD PROCESS**

The BICD process begins with the customer need ( $Ne$ ) and finishes with concept of the expected biorobot (CBR). Thus, the process input is  $Ne$  and output is  $CBR$ . During the process, information inputs ( $I_2, I_3, I_5$ ) and output ( $I_4$ ) are also observed. If it is assumed that the BICD process is a system, all inputs and outputs of this system can be systematically represented with classic DEVS coupled model as presented in this chapter.

The coupled model includes the classic DEVS atomic models of the six states; task clarifying ( $S_1$ ), biological system selecting ( $S_2$ ), biological system analyzing ( $S_3$ ), bioinspired transformation ( $S_4$ ), engineering structures generalization ( $S_5$ ), engineering structures selection ( $S_6$ ) are applied in the BICD process and each of them was modeled in Section 4.4.2 based on the definitions in Section 3.3.

The classic DEVS atomic models of the states show that sixteen sub-states are obtained through the BICD process. Figure 4.15 (based on Figure 4.3) depicts the general representation of the BICD process model including states and their sub-states. Case studies which are performed to develop DEVS model are explained in detail in Chapter 5.

According to the observations during the mathematical derivation of the model, it is determined that the DEVS is not the “best” model for development of the BICD process model. Although the DEVS model allows the designer to observe the effects of inputs on the final design, the obtained effects are not clear. Thus, in order to provide more effective sight of the final design concept during the process, a better modeling tool is tried to be developed. Within that context, a model alternative, Functional Model (a Forrester Diagram approach), is applied to represent the BICD process. Some differential equations are derived to demonstrate relations between steps, inputs and outputs of the BICD process, but significant results have not been obtained. The application details are summarized in Appendix B.

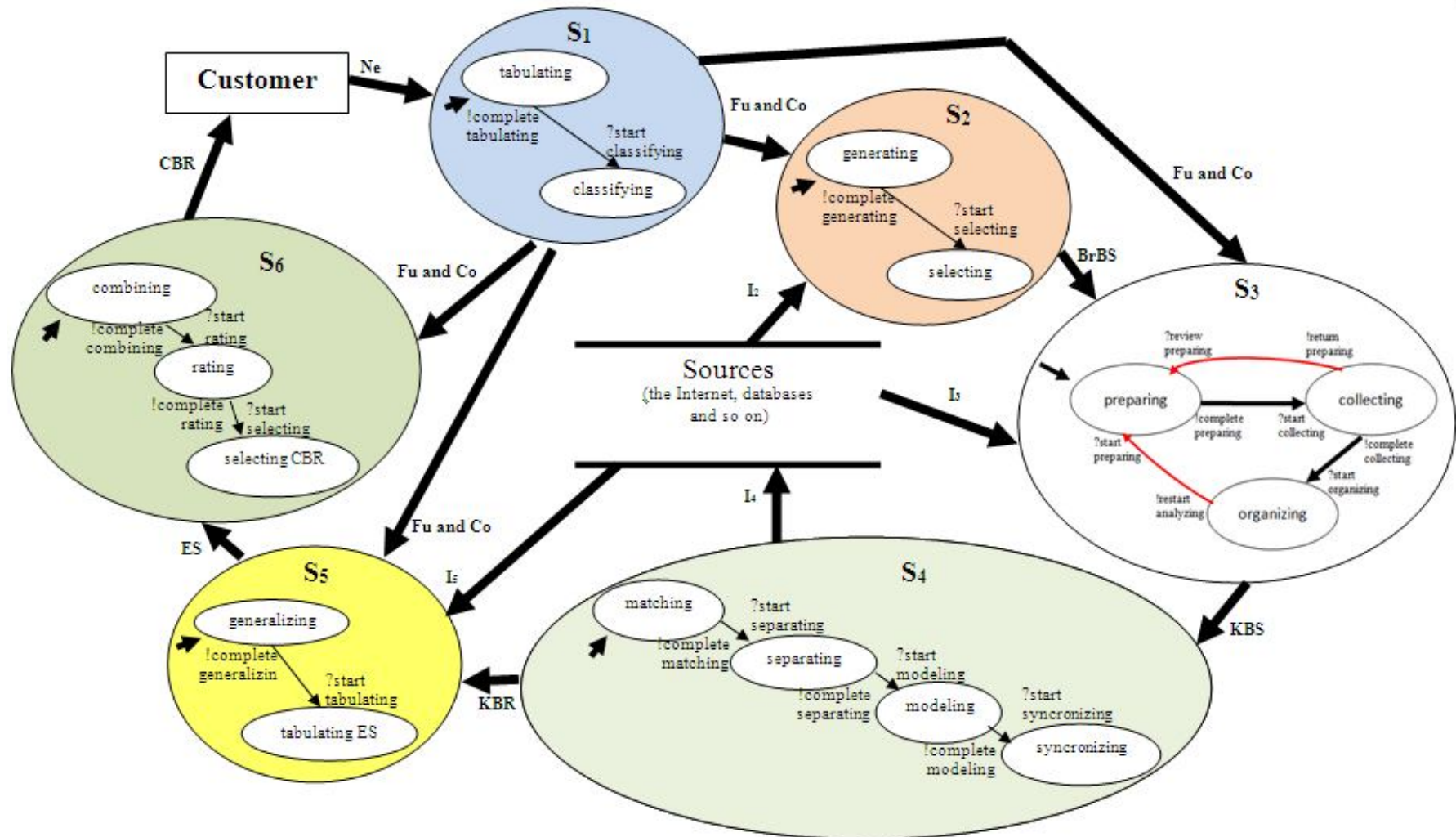


Figure 4.15 Model representation of the BICD process

## CHAPTER 5

### CASE STUDIES OF THE BICD PROCESS

In Chapter 3 and Chapter 4, the developed BICD process and its DEVS model are explained. In this research, the BICD process has been applied to several case studies and is presented in detail in Chapter 5.

In this study, fourteen biological systems have been investigated and four of them are presented in this chapter. In Section 5.1, the reasons for the selection of four case studies are stated. Section 5.2 gives the case studies which are *dog biorobot (BioDog)*, *cockroach biorobot (BioCoc)*, *jumping biorobot* and *hybrid biorobot*. The BioDog and cockroach biorobot are solution-based (SB) and their preliminary prototypes have also been manufactured. Jumping biorobot and hybrid biorobot are problem-based (PB) and hybrid biorobot has been designed with inspiration from multiple biological systems. All abbreviations used in this chapter are tabulated in the List of Abbreviations.

#### 5.1 BIOLOGICAL SYSTEMS INVESTIGATED IN THE RESEARCH

Throughout this research study, fourteen (14) different biological systems and their twenty four (24) different locomotion types have been investigated. They are classified according to locomotion types or actuator features and this classification is given in Figure 5.1. Six of these biological systems have been studied for the BICD process; these are cockroach, dragonfly, dog (walking and trotting locomotion), grasshopper, lobster and human. Thus, six biological systems and their seven locomotion types have been investigated for the BICD process.

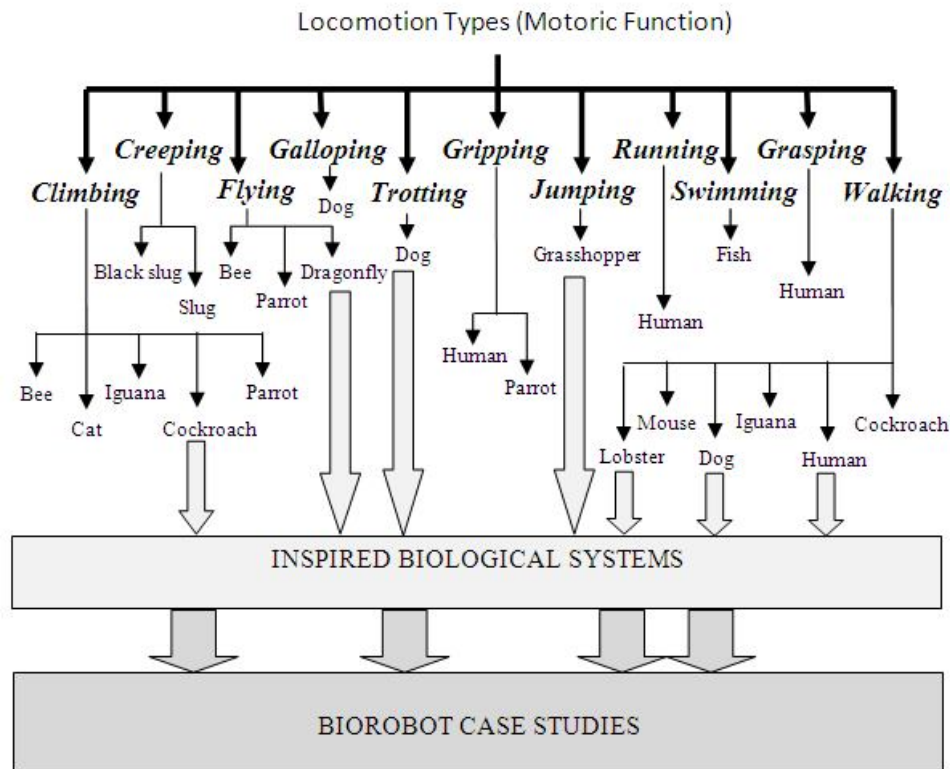


Figure 5.1 Biological systems investigated and/or inspired in the dissertation

Table 5.1 provides a list of the biological systems investigated in this research and data collecting (analysis) methods for each system. The literature survey (content analysis method) provides information about three of the biological systems although the others were investigated using both literature survey and observation method. In this research, an experimental set-up of observation method, including a Photron Fastcam MC-2 Color 10K high speed camera with Navitar TV zoom 8.5 - 51 mm lens, two Megaman 60 W cold lighters, has been used to observe biological systems' functions and behaviors. The movements of the limbs of the biological system under observation are recorded with the fast camera system and the collected observation data have been analyzed to obtain the kinematic data for the interested limb of the biological system via TEMA Motion® 2D software.

Table 5.1 Biological systems investigated and/or inspired in the research

<b>Biological System Investigated in the dissertation</b>	<b>Observed Function</b>	<b>Data Collection (Analysis) Method</b>	<b>Quality of video records (if there is)</b>	<b>Biological Systems Inspired for Case Studies</b>	<b>Inspired Functions</b>	<b>Conceptual Design and/or Prototype</b>
Black slug	- Creeping	Observation and Literature	Medium			
Bee	- Flying - Climbing	Observation and Literature	Low			
Cat	- Climbing	Observation and Literature	Medium			
Cockroach	- Climbing - Walking	Observation and Literature	High	Cockroach	- Climbing	Prototype
Dog	- Walking - Trotting - Galloping	Observation and Literature	High	Dog	- Walking - Trotting	Prototype
Dragonfly	- Flying	Literature	NA	Dragonfly	- Flying	Prototype
Fish	- Swimming	Observation and Literature	Low			
Grasshopper	- Jumping	Literature	NA	Grasshopper	- Jumping	Conceptual Design
Human	- Gripping - Grasping - Walking - Running	Observation and Literature	High	Human	- Walking	Prototype
Iguana	- Walking - Climbing	Observation and Literature	High			
Lobster	- Walking	Literature	NA	Lobster	- Walking	Conceptual Design
Mouse	- Walking	Observation and Literature	Medium			
Parrot	- Flying - Gripping - Climbing	Observation and Literature	High			
Slug	- Creeping	Observation and Literature	Medium			

Four of the investigated biological systems were used for the application purpose of developed biorobot design concepts. Some selection criteria have been considered to choose these biological systems. Firstly, jointed-leg biological systems have been selected to reduce the required time to analyze the biological systems. Second criterion is the resolution of video records of the high speed camera because during the analysis, joints should be followed. Thirdly, the human leg and the dragonfly case studies have been performed by senior undergraduate students, thus they are not included in the dissertation. Four biological system and their five locomotion types

have been studied for four case studies of the BICD process. Details of the selected case studies are presented in Section 5.2.

## **5.2 CASE STUDIES**

Four case studies have been implemented with the BICD process. These case studies are *dog biorobot (BioDog)*, *cockroach biorobot (BioCoc)*, *jumping biorobot* and *hybrid biorobot*. Although the output of the BICD process is conceptual design of a biorobot, prototypes of two case studies (BioDog and BioCoc) have been manufactured for demonstration purposes. The concept designs of the others: jumping biorobot and hybrid biorobot were completed with the PB approach. Although two PB and two SB case studies are given separately, the only difference between them is the starting point of the design. While the biological system is known at the beginning of the design process for the SB, the imitated biological system is unknown at the beginning for the PB; it is decided during the process. Case studies and their imitated locomotion types are listed below.

1. Dog biorobot (BioDog) for two modes: walking and trotting (SB and prototype),
2. Cockroach biorobot (BioCoc) for climbing (SB and prototype),
3. Jumping biorobot for jumping (PB and conceptual) and
4. Hybrid biorobot for walking (PB and conceptual).

### **5.2.1. Dog Biorobot (BioDog)**

At the beginning of the study, it is assumed that the customer states: “I need a robot which can walk and trot on an indoor smooth surface like a dog. It looks like a small dog. The robot should be light and compact. I have some servo motors and an Arduino platform; we can use them in its prototype....”

In this case study, the customer need is transformed to a concept of BioDog by using the BICD process. During the presentation of the case study, all steps of the BICD DEVS model are given for the BioDog as follows.

### A. Classic DEVS coupled model of the BICD process for the BioDog

The coupled DEVS specification of the BICD process for a BioDog with walking and trotting locomotion is given in Equation 5.1. In Equation 5.1, the eight tuple are same with the equations given in Section 4.4.1 (Equations from 4.7 to 4.14). The differences can be obtained in the classic DEVS atomic models of the states.

$$N_{\text{BICD}}^{\text{BioDog}} = \{X, Y, D, \{M_d \mid d \in D\}, \text{EIC}, \text{EOC}, \text{IC}, \text{Select}\} \quad (5.1)$$

### B. Classic DEVS atomic model of the states of the BICD process for the BioDog

Classic DEVS atomic model of each state is given as follows.

#### i. Task Clarifying ( $S_1$ )

Atomic DEVS model of  $S_1$  is given in Equation 4.14. As it was explained in Section 4.4.2, the input of  $S_1$  is  $Ne$  and  $Ne$  for BioDog is given in Equation 5.2. The requirements list for the BioDog is completed in this state and the list is given in Table 5.2.

$$Ne = \{\text{dog, walking, trotting, small, light, compact, dog-like appearance, include servo motors, include Arduino, indoor area, smooth surface}\} \quad (5.2)$$

Table 5.2 The requirements list of the BioDog

Main Headings		Requirement List
Type of the Biological System		Animal
Species of the Biological System (if specified)		Dog
Morphology of the final product		Dog-like appearance
Expected Function of the Final Product	Motoric	Walking Trotting
	Sensoric	-
	Cognitive	-
Specified Expected Features		servo motors, Arduino, compact, light
Operational Environment		Indoor, smooth surface
Cost		-
Schedule		-

In this state, the  $Fu$  and  $Co$  for the BioDog are classified based on the requirements list and represented in Equation 5.3 and Equation 5.4. As shown in Equation 5.3 and stated in Section 3.3.1,  $Fu$  includes the information about types of locomotion. As shown in Equation 5.4 and explained in Section 3.3.1,  $Co$  covers six terms which are represented in the Equations 5.5 to 5.10.

$$Fu = \{\text{walking, trotting}\} \quad (5.3)$$

$$Co = \{\text{SBS, Mor, Spe, OpE, Cos, Sce}\} \quad (5.4)$$

$$\text{SBS} = \{\text{dog}\} \quad (5.5)$$

$$\text{Mor} = \{\text{App, Siz, Weh, Heh, NuL}\} \quad (5.6)$$

$$= \{\text{dog-like, small, 4}\}$$

$$\text{Spe} = \{\text{servo motors, Arduino, compact, light}\} \quad (5.7)$$

$$\text{OpE} = \{\text{indoor area, smooth surface}\} \quad (5.8)$$

$$\text{Cos} = \emptyset \quad (5.9)$$

$$\text{Sce} = \emptyset \quad (5.10)$$

Equations 4.23 to 4.25 gave the expiration times of each sub-state. “Tabulating Ne” has been completed in one day and “classifying” has been done in one day;  $t_i$  and  $t_{i+1}$  are first and second days. Hence, the first step/state of the BICD process has been completed in two days.

## ii. Biological System Selecting ( $S_2$ )

Atomic DEVS model of “Biological System Selecting” state was given in Equation 4.26. In this state,  $I_2$  is the set of information about the breed of the dog and it is examined in Equation 5.11 according to the Internet source [Dog-breed-selector, 2012].

$$I_2 = \{\text{Terrier, Alaskan Malamute, Afghan Hound, English Cocker Spaniel, Affenpinscher, American Eskimo Dog and so on}\} \quad (5.11)$$

In this case study, as given in Equation 5.12, a Terrier dog is selected for walking and trotting locomotion on an indoor and smooth surface based on  $Fu$  and  $Co$ . Thus,  $BrBS$  is a 3.7 kg terrier dog. Figure 5.2 gives the picture of the selected Terrier dog.

$$\lambda_2 (\text{“selecting BS”}, t_{i+3}) = BrBS = \text{“Terrier dog”} \quad (5.12)$$



Figure 5.2 Selected terrier dog

In Section 4.4.2, Equations 4.36 to 4.39 gave the expiration times of each sub-state. “Generating” has been completed in two days and “selecting BS” has been done in one day;  $t_{i+2}$  and  $t_{i+3}$  are fourth days and fifth days. It means that the initial two states/stages of the BICD process have been performed in five days.

### iii. Biological System Analyzing ( $S_3$ )

Atomic DEVS model of “Biological System Analysis” state was given in Equation 4.56. As represented in Section 4.4.2, four sub-states are considered in this state. In “preparing” sub-state, the designer selected both the observation method and content analysis method (literature survey) to analyze the terrier dog. In “collecting” sub-state, the designer collects data about the dog by using the two methods. In this case study, the content analysis method has been performed  $I_3$  which is information about the selected terrier dog collected from the literature while observation method has been realized with an experimental set-up shown in Figure 5.3.a. The GUI (graphical user interface) of the camera’s software (PFV- Photron FASTCAM Viewer) is displayed in Figure 5.3.b. 2D video records were collected during the experiment because of the body symmetry and negligible angular changes in the third axis.

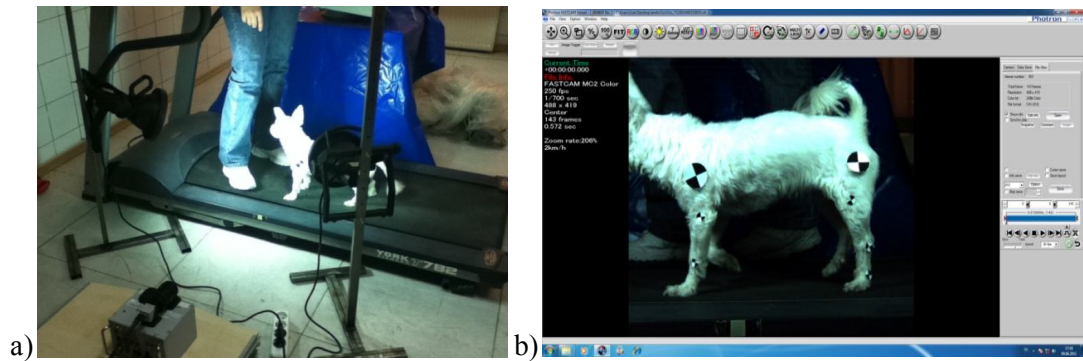


Figure 5.3 Pictures of a) the experimental set-up and b) the GUI of PFV

In the experiment, markers are attached at the joints of shoulder, elbow, wrist, hips, knee, ankle and end of the hind paw of the dog as shown in Figure 5.3.b. Then, the dog was made to walk on a treadmill. Experiments with different walking speeds show that the dog displays similar walking and trotting behaviors at 1 km/h and 2 km/h. These videos were recorded with 1000 FPS and 512 x 512 pixels by using the high speed camera. During the experiment, documentary (content) analysis has been applied and particularly morphological data of the terrier dog (such as bone and joint structures) has been collected from the literature. In this case study, a few iterations between “collecting” and “preparing” have been performed because of decisions about places of markers and speeds of walking and trotting.

In the “organizing” sub-state, video records of the dog has been analyzed. The GUI of the software is given in Figure 5.4. In this program, markers have been tracked and joint angles versus time have been tabulated and represented by graphs. At the end of the “organizing” sub-state, it is decided to return to the “preparing” sub-state as represented in Equation 5.45 because of the reason that 1000 FPS is too high for the records. In the “preparing” sub-state, the frame rate has been selected as 250 FPS and experiments have been repeated once more. The final video records have been analyzed and new discrete data sets for joint angles have been generated again.

As represented in Chapter 3 and Chapter 4, the *KBS* includes *MorBS*, *FuBS* and *BeBS*. In Section 3.3.3, all details about the *MorBS*, *FuBS* and *BeBS* were explained. In this case, *MorBS* has been discussed for the terrier dog and systematically represented in Equation 5.13 to 5.25.



Figure 5.4 The GUI of the TEMA Motion® 2D software

$$\text{MorBS} = \{\text{DiBS}, \text{WeBS}, \text{NuL}, \text{PaL}, \text{LoL}, \text{FoLb}, \text{JoL}, \text{ToJo}, \text{SoM}\} \quad (5.13)$$

$$\text{DiBS} = \{\text{Height} = 28 \text{ cm}, \text{Width} = 49 \text{ cm}\} \quad (5.14)$$

$$\text{WeBS} = \{3.7 \text{ kg}\} \quad (5.15)$$

$$\text{NuL} = \{4\} \quad (5.16)$$

$$\text{PaL} = \{\text{fore legs}, \text{hind legs}\} \quad (5.17)$$

$$\text{LoL}_{\text{fore}} = \{\text{Scapula}, \text{Humerus}, \text{Radius and Ulna}, \text{Forepaw}\} \quad (5.18)$$

$$\text{LoL}_{\text{hind}} = \{\text{Femur}, \text{Tibia and Fibula}, \text{Hindpaw}\} \quad (5.19)$$

$$\text{FoLb} = \{\text{FO}_{\text{Scapula}}, \text{FO}_{\text{Humerus}}, \text{FO}_{\text{Radius\&Ulna}}, \text{FO}_{\text{Forepaw}}, \\ \text{FO}_{\text{Femur}}, \text{FO}_{\text{Tibia\&Fibula}}, \text{FO}_{\text{Hindpaw}}\} \quad (5.20)$$

$$\text{JoL}_{\text{fore}} = \{\text{shoulder}, \text{elbow}, \text{wrist}\} \quad (5.21)$$

$$\text{JoL}_{\text{hind}} = \{\text{hips}, \text{knee}, \text{ankle}\} \quad (5.22)$$

$$\text{ToJo}_{\text{fore}} = \{\text{Glenohumeral joint}, \text{Ginglymus}, \text{Distal radioulnar} \\ \text{articulation (inferior radioulnar joint)}\} \quad (5.23)$$

$$\text{ToJo}_{\text{hind}} = \{\text{Acetabulofemoral joint}, \text{Compound joint}, \\ \text{Talocrural joint (Synovial)}\} \quad (5.24)$$

$$\text{SoM} = \emptyset \quad (5.25)$$

In Equation 5.20,  $Fo$  represents the forms of a limb. The forms and the measured dimensions of the terrier dog limbs are tabulated in Table 5.3. The sketches are collected from a web page [Real3danatomy, 2012].

$FuBS$  is function of the biological system and it is a part of the  $KBS$ . In this case study, walking and trotting functions of the terrier dog have been investigated. The classified  $FuBS$  is given in Equation 5.26.

$$FuBS = \{ \text{walking} = 1 \text{ km/h, trotting} = 2 \text{ km/h,} \quad (5.26)$$

$$\text{joint angles\_walking, joint angles\_trotting} \}$$

In Equation 5.26, “joint angles\_walking” and “joint angles\_trotting” represent joint angles versus time for walking and trotting locomotion types. Joint angles of the dog’s fore leg and hind leg exhibited during walking and trotting are shown in the graphs of Figure 5.5 and Figure 5.6.

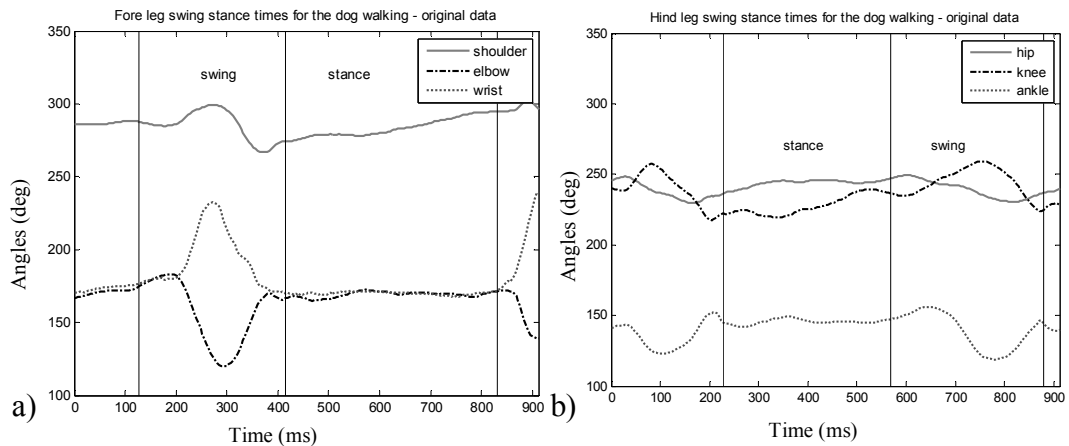


Figure 5.5 Joint angles of the dog’s a) fore leg and b) hind leg for walking

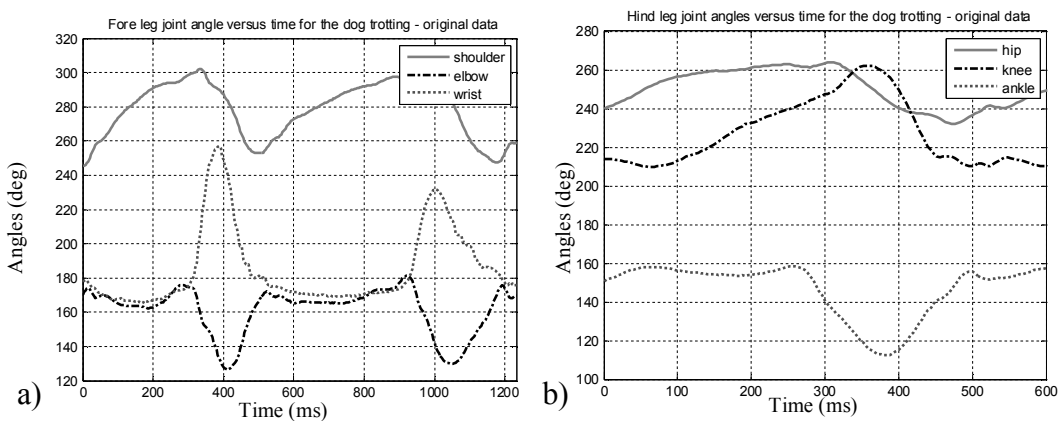









Figure 5.6 Joint angles of the dog’s a) fore leg and b) hind leg for trotting

Table 5.3 Forms/Structures of limbs of a dog

Limbs	Forms [Real3danatomy, 2012]	Measured maximum lengths of the Terrier dog limbs
Scapula		6 cm
Humerus		5 cm
Radius and Ulna		13 cm
Forepaw		
Femur		10 cm
Tibia and Fibula		15 cm
Hindpaw		

*BeBS* is the behavior of the biological system and it is also a part of the *KBS*. *BeBS* of the Terrier dog is summarized in Equation 5.27. When a dog walks on a smooth surface, each leg has different swing-stance times; there is no matched leg (none of the legs moves with any other) during walking. However, during trotting, the dog's left and right legs separately move together. In Equation 5.27, "walking legs combination" and "trotting legs combination" represent the dog's legs combination which exhibits the behavior of the dog. The leg combinations are illustrated in Figure 5.7 and Figure 5.8 where R and L show right and left legs and 1 and 2 symbolize fore and hind legs. Stance phases of each leg are represented by black ellipses.

$$\text{BeBS} = \{\text{walking} = \text{no matching for the legs, trotting} = \text{left\_right matching, walking legs combination, trotting legs combination}\} \quad (5.27)$$

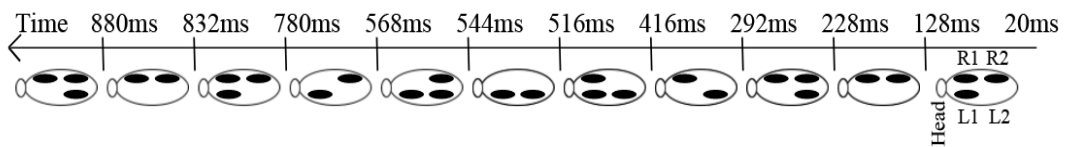


Figure 5.7 Legs combination during dog walking

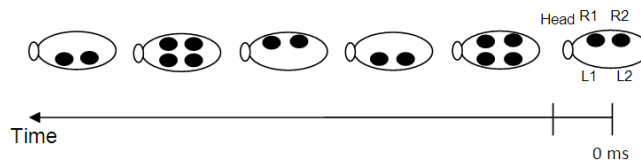


Figure 5.8 Legs combination during dog trotting

Equation 4.52 to 4.55 represented the expiration times of each sub-state of  $S_3$ . If "preparing" has been completed in two days, "collecting" has been performed in five days and "organizing" has been done in 5 days,  $t_{i+4}$ ,  $t_{i+5}$  and  $t_{i+6}$  are seventh, twelfth and seventhth days, respectively. It means that "biological system analysis" state has been performed in twelve days, so the initial three states/stages of the BICD process have been completed in seventeen days.

#### iv. Bioinspired Transforming (S<sub>4</sub>)

In “Bioinspired Transforming” state, the *KBS* of biological domain is transformed into *KBR*. *KBR* represents a set of knowledge about the biorobot (BioDog) in engineering domain. The general atomic DEVS model of this state was given in Equation 4.56.

As described in Section 4.4.2, the S<sub>4</sub> includes four sub-states. In “matching”, each form and joint structure of the biological system has been matched with known engineering forms and structures. For this case study, the “matching” for the Terrier dog is shown in Table 5.4 and Table 5.5. Dimensions of the engineering structures have been obtained experimentally from the preliminary prototype of the BioDog. Systematic “scaling” is not considered in this research. The “scaling” for biorobots can be considered as a future work.

Table 5.4 The matched joint structures of the Terrier dog








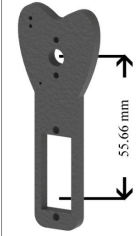

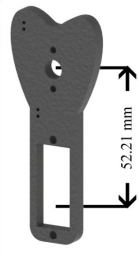

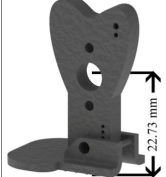

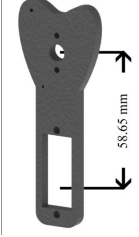

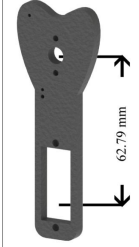

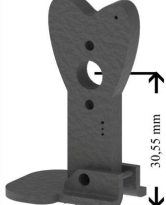
Legs	Joint name	Joint type		Sketch of the joint [Wikipedia_joint, 2012]
		Biological	Engineering	
Front Legs	Shoulder	Glenohumeral Joint	Ball and Socket	
	Elbow	Ginglymus	Hinge Joint	
	Wrist	distal radioulnar articulation (inferior radioulnar joint)	Pivot Joint	
Hind legs	Hips	Acetabulofemoral Joint	Ball and Socket	
	Knee	Compound Joint	Hinge Joint	
	Ankle	Talocrural Joint (Synovial)	Hinge Joint	

Table 5.5 The matched forms/structures of the Terrier dog

Limbs	Forms [Real3danatomy, 2012]	Measured maximum lengths of the Terrier dog	Matched Engineering Form/Structure
Humerus		5 cm	
Radius and Ulna		13 cm	
Forepaw			
Femur		10 cm	
Tibia and Fibula		15 cm	
Hindpaw			

In the “matching”, some major assumptions have been done for the BioDog. These are listed as follows.

1. All joints of the dog legs have been assumed as hinge joints because of the negligible angular changes in the third dimension.
2. The scapula is fixed in the body, so the joint of scapula has been neglected.
3. Radius and Ulna have been designed together as a link.
4. Tibia and Fibula have been designed together as a link.

In “separating”, a locomotion cycle of BioDog has been brought out. This cycle covers a stance (contact with the ground) and swing (no contact with the ground) phases and each leg repeats its own cycle. For walking locomotion, Figure 5.5 was rearranged for the locomotion cycle and it is displayed in Figure 5.9 where the “stance” and “swing” phases are considered for the left legs. A similar approach has been applied for trotting and the joint angles versus time graph is given in Figure 5.10.

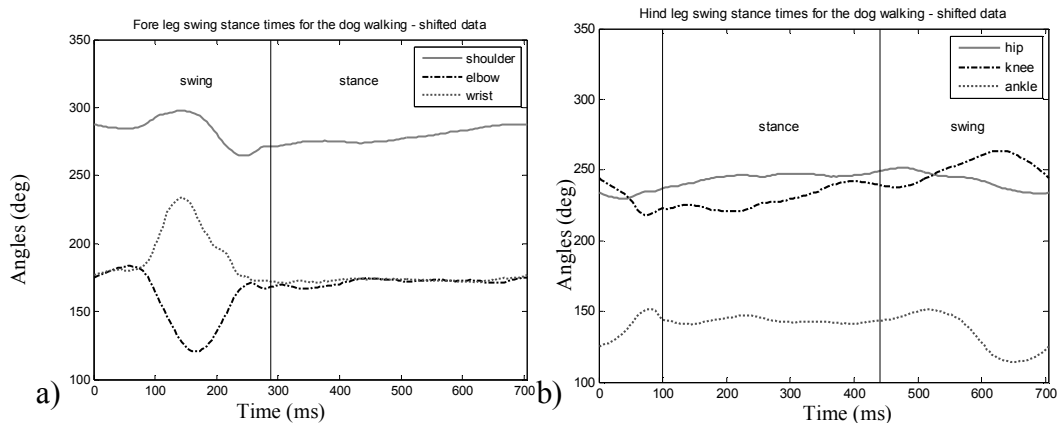


Figure 5.9 Walking locomotion cycle of the BioDog for a) fore leg b) hind leg.

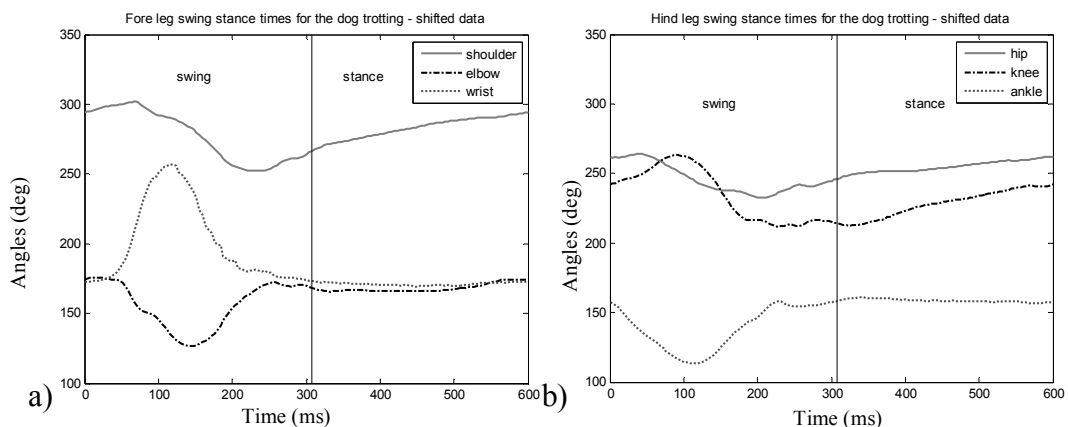


Figure 5.10 Trotting locomotion cycle of the BioDog for a) fore leg b) hind leg.

Biological systems are flexible systems, so they do not actually follow a locomotion cycle. In “modeling” sub-state, joint angles have been switched linearly around the initial angle in order to complete the locomotion cycle for the BioDog. Thus, a synchronous motion has been developed for the biorobot. Figure 5.9 and Figure 5.10 demonstrate the shifted joint angles.

If mathematical models for joint angles have been required, curve fitting methods could be applied. In this case study, discrete data sets have been used to drive the servo motors with an Arduino platform, so mathematical models of joint angles have not been derived.

The “modeling” gives the behavior of the Terrier dog during the locomotion cycles of walking and trotting. The walking and trotting behavior in a locomotion cycle are shown in Figure 5.11 and Figure 5.12 where R and L show right and left legs and 1 and 2 symbolize fore and hind legs. Stance phases of each leg are represented by black ellipses.

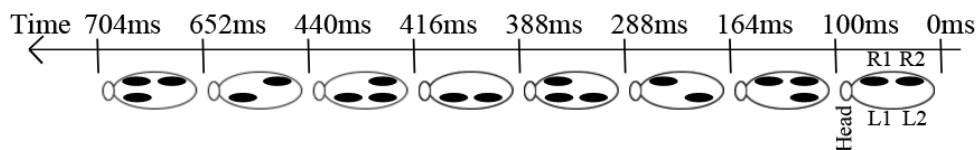


Figure 5.11 A walking cycle for the BioDog

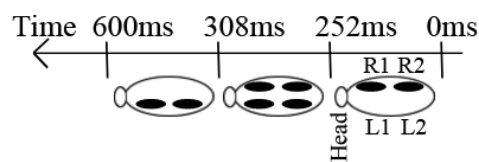


Figure 5.12 A trotting cycle for the BioDog

When the designer completes “modeling” sub-state, s/he starts “synchronizing” (Equation 5.77). In “synchronizing”, the left leg joint data set of the locomotion cycle is synchronized with the right legs, so the two-dimensional (2D) locomotion model is transformed into a three-dimensional (3D) model.

The outputs of the  $S_4$  are  $KBR$  and  $I_4$ . The  $KBR$  is represented in Equation 5.28. Each component of the  $KBR$  is detailed in Equation 5.29 to 5.38.  $I_4$  is a set of information

about the analyzed dog and it is represented in the engineering perspective given in Equation 5.39. In this case, it is seen that  $I_4$  is a general form of the  $KBR$ .

$$KBR = \{MorBR, FuBR, BeBR\} \quad (5.28)$$

$$MorBR = \{NuL, PaL, LoL, FoLb, JoL, ToJo\} \quad (5.29)$$

$$NuL = \{4\} \quad (5.30)$$

$$PaL = \{\text{fore, hind}\} \quad (5.31)$$

$$LoL_{\text{fore}} = \{\text{humerus, radius, paw}\} \quad (5.32)$$

$$LoL_{\text{hind}} = \{\text{femur, tibia, paw}\} \quad (5.33)$$

$$FoLb = \{FO_{\text{humerus}}, FO_{\text{radius}}, FO_{\text{forepaw}}, FO_{\text{femur}}, FO_{\text{tibia}}, FO_{\text{hindpaw}}\} \quad (5.34)$$

$$JoL = \{\text{shoulder, elbow, wrist, hips, knee, ankle}\} \quad (5.35)$$

$$ToJo = \{\text{joints} = \text{hinge joints}\} \quad (5.36)$$

$$FuBR = \{\text{walking} = 1 \text{ km/h speed, trotting} = 2 \text{ km/h,} \\ \text{dynamic model of walking, dynamic model of trotting}\} \quad (5.37)$$

$$BeBR = \{\text{no matching legs for walking, legs are matched and right legs} \\ \text{are matched for trotting, walking leg combination, trotting leg} \\ \text{combination}\} \quad (5.38)$$

$$I_4 = \{\text{limbs}=\text{links, joints}=\text{hinge joints, joint angles for a walking cycle,} \\ \text{leg combinations for a walking cycle}\} \quad (5.39)$$

In Equation 5.34,  $Fo$  represents the form of a limb and the forms/structures of the BioDog, which were also tabulated in Table 5.5. In the equation of the  $FuBR$  (Equation 5.37), dynamic models are based on joint angles for a locomotion cycle and they were given in Figure 5.9 and Figure 5.10. In Equation 5.38, leg combinations were illustrated in Figure 5.11 and Figure 5.12.

Equations 4.69 to 4.73 show the expiration times of each sub-state of  $S_4$ . If “matching” sub-state has been completed in two days, “separating” sub-state has been done in one day, “modeling” sub-state has been performed in two days and

“synchronizing” sub-state has been finished in 1 day,  $t_{i+7}$ ,  $t_{i+8}$ ,  $t_{i+9}$  and  $t_{i+10}$  are ninth, twentieth, twenty second and twenty third days, respectively. It means that “bioinspired transformation” state has been implemented in six days, so the first four design steps/states have been completed in twenty three days.

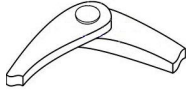

#### v. Engineering Structure Generalizing ( $S_5$ )

In “Engineering Structure Generalizing” state, engineering structures are generated based on the  $KBR$ ,  $Fu$ ,  $Co$  and the information about alternatives of the engineering structures ( $I_5$ ). The atomic DEVS model of  $S_5$  was given in Equation 4.75. The general form of the  $I_5$  is shown in Equation 5.40.

$$I_5 = \{\text{actuator alternatives, material alternatives, joint structure alternatives, controller alternatives}\} \quad (5.40)$$

The output of this state is  $ES$  of the BioDog. Using servo motors and Arduino platform is the constraint of the design and stated by the customer, so alternatives for  $FuBR$  and  $BeBR$  were not generated in this case study. For  $MorBR$ , several material and joint alternatives were generated and given in Table 5.6. The  $ES$  is summarized in Equation 5.41.

Table 5.6 The Morphological Matrix of the BioDog

		Alternatives		
		1	2	3
MorBR	Limbs (Links)	Plexiglass	Aluminum	Steel
	Joints (Hinge joints)	Pin type 	Embedded type 	x
FuBR	Actuator	Servo motors	x	x
	Controller	Arduino	x	x
BeBR	Controller	Arduino	x	x

$$ES = \{\text{Plexiglass, Aluminum, Steel, Pin type, Embedded type, Servo motors, Arduino}\} \quad (5.41)$$

In Table 5.6 and Equation 5.41, two alternatives for joint structures are examined; these are pin type and embedded type. Pin type is selected as a hinge joint type and it joins two limbs/links with a pin preventing the translational motion. Embedded type represents a hinge joint type whose form is close to the biological system. The joint types are illustrated in Table 5.6.

Equations 4.83 to 4.85 gave the expiration times of each sub-state of  $S_5$ . If “generalizing” sub-state has been completed in 1 day and “tabulating” sub-state has been finished in 1 day,  $t_{i+1}$  and  $t_{i+2}$  are 24th and 25th days. It means that “engineering structure generalizing” state has been performed in 2 days.

#### vi. Engineering Structure Selecting ( $S_6$ )

The atomic DEVS model of the “Engineering Structure Selecting” was represented in Equation 4.86. In this state, concept alternatives for the BioDog are generated by using the *ES* and a design concept is selected as the *KBR*. The selection is realized based on *Fu* and *Co*.

Three sub-states of this state are “combining”, “rating” and “selecting CBR” In “combining” sub-state, concept alternatives of the BioDog have been generated and given in Table 5.7. For design of the BioDog, six concept alternatives are considered.

Table 5.7 The BioDog concept alternatives

	<b>Material of links</b>	<b>Joint</b>	<b>Actuator</b>	<b>Controller for FuBR</b>	<b>Controller for BeBR</b>
$C_1$	Plexiglass	Pin-type	Servo motor	Arduino	Arduino
$C_2$	Plexiglass	Embedded-type	Servo motor	Arduino	Arduino
$C_3$	Aluminum	Pin-type	Servo motor	Arduino	Arduino
$C_4$	Aluminum	Embedded-type	Servo motor	Arduino	Arduino
$C_5$	Steel	Pin-type	Servo motor	Arduino	Arduino
$C_6$	Steel	Embedded-type	Servo motor	Arduino	Arduino

In the “rating”, the evaluation criteria are considered and rated based on *Fu* and *Co*. The evaluation criteria of the BioDog are derived from the constraints and are listed below.

- High dog-like appearance,
- Small size,

- High compactness and
- Light weight.

After the selection of evaluation criteria, weights for each criterion are assigned by the designer. Then, each concept are rated as unsatisfactory, just tolerable, adequate, good or very good using an ordinal scale such as 0, 1, 2, 3 or 4 according to evaluation criteria. Finally, each concept rating is multiplied by its respective weight and summed to produce an overall rating for the concept. These steps for Weighted Rating Method were done and shown in Table 5.8. Selection of the evaluation criteria and rates of them are manually decided by the designer. Automatic conduction of selection and rating should be implemented in the process which is suggested as a future work.

In “selecting CBR”, a concept of biorobot (CBR) is selected according to the overall rating. As shown in Table 5.8, the concept of C<sub>1</sub> has been selected for the BioDog design and given in Equation 5.42.

Table 5.8 Weighted Rating Method for evaluation criteria of the BioDog

(Rating: Unsatisfactory = 0, Just tolerable = 1, Adequate = 2, Good = 3, Very good = 4 and NA = not applicable)

Criteria	Importance Weight (%)	Concept Alternatives											
		C <sub>1</sub>		C <sub>2</sub>		C <sub>3</sub>		C <sub>4</sub>		C <sub>5</sub>		C <sub>6</sub>	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
High dog-like appearance	25	4	1.00	4	1.00	2	0.50	2	0.50	2	0.50	2	0.50
Small size	25	4	1.00	3	0.75	3	0.75	3	0.75	2	0.50	2	0.50
High compactness	15	4	0.60	4	0.60	3	0.45	3	0.45	2	0.30	2	0.30
Light weight	35	4	1.40	3	1.05	3	1.05	2	0.70	2	0.70	1	0.35
Total	100	NA	4.00	NA	3.40	NA	2.75	NA	2.40	NA	2.00	NA	1.65

$$\begin{aligned}
 \text{CBR} = \{ & \text{material} = \text{flexiglass, joints} = \text{pin-type,} \\
 & \text{actuators} = \text{servo motors, controller}_1 = \text{controller}_2 = \text{Arduino} \}
 \end{aligned}
 \tag{5.42}$$

Equations 4.99 to 4.102 represented the expiration times of each sub-state of  $S_6$ . If “combining” and “rating” sub-states have been completed in one day and two days, respectively, and “selecting CBR” sub-state has been finished in 1 day,  $t_{i+13}$ ,  $t_{i+14}$  and  $t_{i+15}$  are twenty sixth, twenty eighth and twenty ninth days. It means that the conceptual design of the BioDog has been performed nearly in a month.

In twenty nine days, the concept design of the BioDog has been completed. According to the *CBR*, an initial prototype (Figure 5.13.a) has been produced to demonstrate the system feasibility. Then, to reduce its size and weight, a final prototype of the BioDog has been manufactured in the order shown in Figure 5.13.b. The BioDog prototype simulates the walking and trotting behavior of a dog and these two modes can be switched with a remote control.

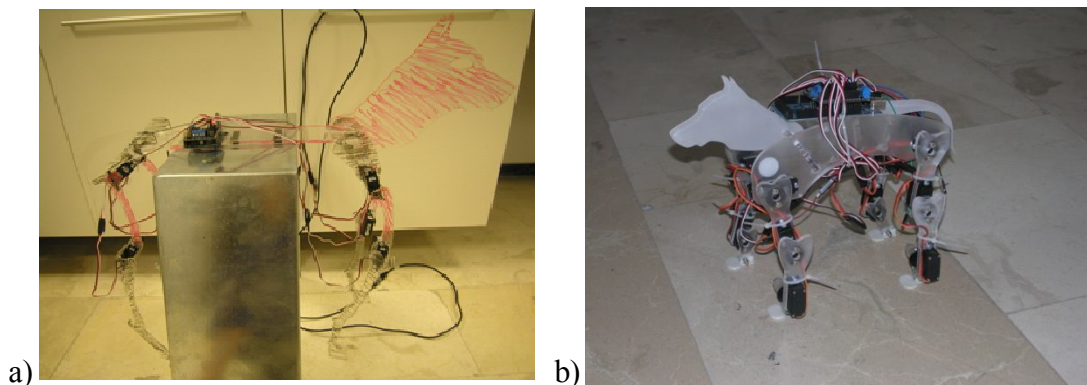


Figure 5.13 A view of a) the initial prototype b) the final prototype of the BioDog

### 5.2.2 Cockroach Biorobot (BioCoc)

In this case study, climbing locomotion of a cockroach has been studied. A prototype of a cockroach biorobot has been designed and produced at the end of this case study.

At the beginning of the design, it is assumed that the customer need is given as the following sentences. “I need a biorobot which can climb on a vertical surface like a cockroach. It looks like a cockroach and its maximum weight should be 1 kg while maximum volume is  $10 \text{ cm}^3$ . ”

The BICD methodology is applied to the conceptual design of the cockroach biorobot as given below.

### i. Task Clarifying ( $S_1$ )

In the  $S_1$ , the customer's needs were firstly tabulated in the requirements list given in Table 5.9. Then,  $Fu$  and  $Co$  are classified based on the list. These are given in Equations 5.43 to 5.50.

Table 5.9 The requirements list of the cockroach biorobot (BioCoc)

Main Headings		Requirement List
Type of the Biological System		Insect
Species of the Biological System (if specified)		Cockroach
Morphology of the Final Product		Cockroach-like appearance Max. 1 kg Max. 10 cm <sup>3</sup>
Expected Function of the final product	Motoric	Climbing
	Sensoric	-
	Cognitive	-
Specified Expected Features		-
Operational Environment		Vertical plexiglass surface ( $\approx 125$ Ra)
Cost		-
Schedule		-

$$Fu = \{\text{climbing}\} \quad (5.43)$$

$$Co = \{\text{SBS, Mor, Spe, OpE, Cos, Sce}\} \quad (5.44)$$

$$\text{SBS} = \{\text{cockroach}\} \quad (5.45)$$

$$\text{Mor} = \{\text{cockroach-like, Max. 10 cm}^3, \text{Max. 1 kg, 6}\} \quad (5.46)$$

$$\text{Spe} = \emptyset \quad (5.47)$$

$$\text{OpE} = \{\text{Vertical plexiglass surface } (\approx 125 \text{ Ra})\} \quad (5.48)$$

$$\text{Cos} = \emptyset \quad (5.49)$$

$$\text{Sce} = \emptyset \quad (5.50)$$

### ii. Biological System Selecting ( $S_2$ )

In this case study, an American cockroach has been selected because this breed of the cockroach can be found easily for the observation analysis method. The output of the  $S_2$  (BrBS) is given in Equation 5.51.

$$\text{BrBS} = \text{"American cockroach"} \quad (5.51)$$

### iii. Biological Systems Analyzing (S<sub>3</sub>)

In this case study, content analysis and observation methods have been used together to collect data about the American cockroach. This process is illustrated in Figure 5.14.

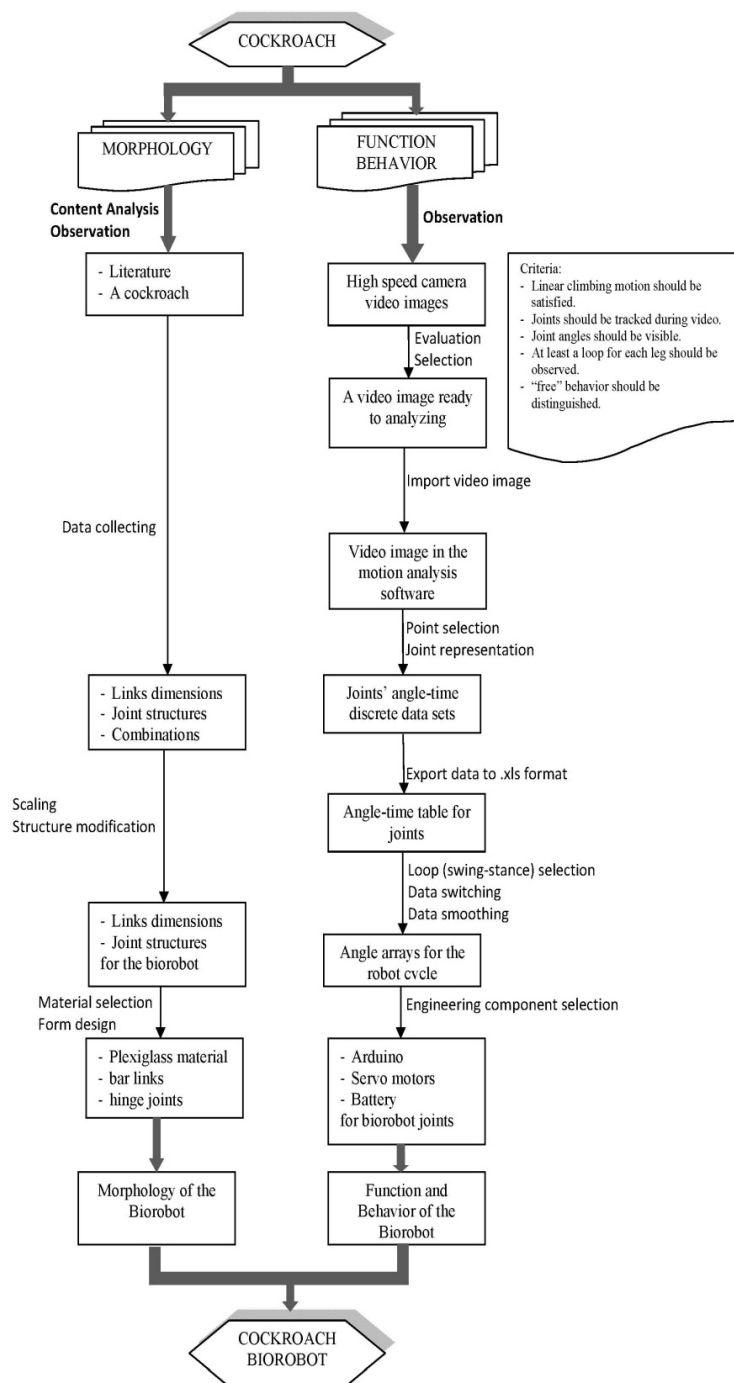


Figure 5.14 A flow representation of the BICD procedure of the cockroach from biological system to biorobot.

In the observation method, the experimental set-up for the cockroach is shown in Figure 5.15. A 0.07 gr in weight and 15.3 mm in length American cockroach has been analyzed in the experiments. The cockroach climbed free on a rectangular plexiglass prism during the experiment and two dimensional videos have been recorded with 1000 FPS and 376 x 484 pixel resolution.

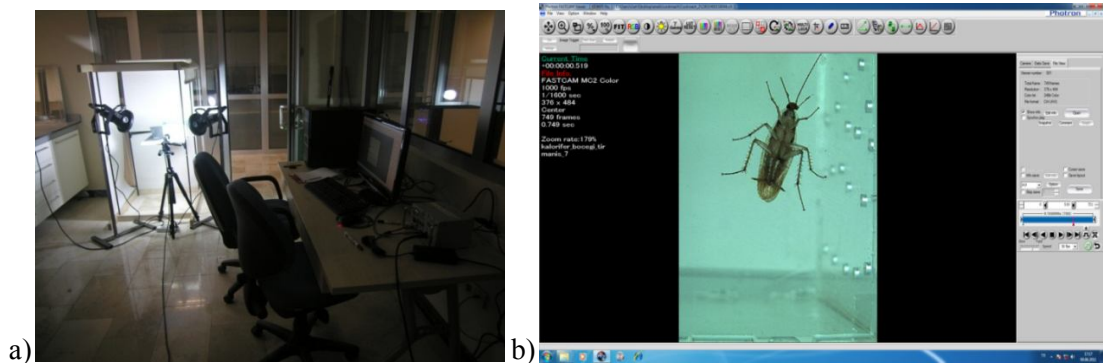


Figure 5.15 Views of a) the experimental set-up b) the PFV for the cockroach climbing

During the experiments, various video images have been recorded; but only one of them is selected for kinematic analysis. Criteria for selecting the video image are given below.

- Climbing on a straight line (linear climbing motion) should be obtained.
- Selected motion analysis program is based on point tracking, so joints should be tracked during the video.
- Joint angles should be clear and visible.
- A climbing loop includes swing (no contact with the ground) and stance (contact with the ground) phases. To construct a valid cycle of climbing of the cockroach, each leg's swing-stance phases should be observed.
- One of the aims of this study is to gather information about behavior in natural environment that can be obtained and visualized "free" behavior.

Knowledge about the American cockroach which was collected from the selected video record and literature survey is given in Equation 5.52.

$$\text{KBS} = \{\text{MorBS}, \text{FuBS}, \text{BeBS}\} \quad (5.52)$$

In Equation 5.52, morphology of the cockroach is abbreviated as *MorBS*. *MorBS* have been collected by using the literature survey and the experimental set-up and it is given in Equations from 5.53 to 5.63.

Studies show that cockroaches have three main body parts; a head, a thorax, and an abdomen. Three pairs of legs; prothoracic (front) legs, mesothoracic (middle) legs, and metathoracic (hind) legs and two pairs of wings are attached to body at the thorax part [Kram et al., 1997]. The legs were numbered as shown in Figure 5.16 where R and L represent right and left legs and 1, 2 and 3 are front, middle and hind legs, respectively. Each pair of legs includes five parts and these are coxa, trochanter, femur, tibia, and tarsus.

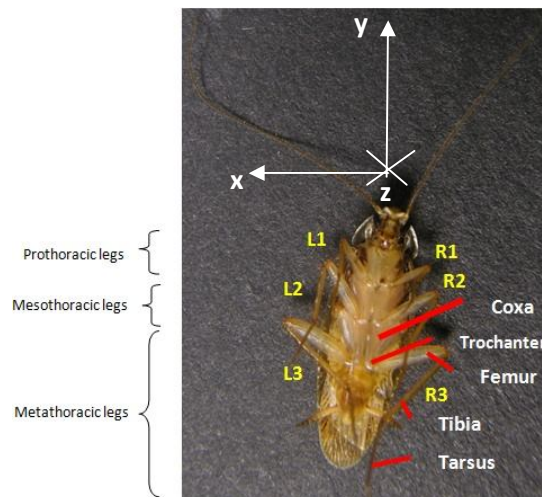


Figure 5.16 Legs and limbs of an American Cockroach

$$\text{MorBS} = \{\text{DiBS}, \text{WeBS}, \text{NuL}, \text{PaL}, \text{LoL}, \text{FoLb}, \text{JoL}, \text{ToJo}, \text{SoM}\} \quad (5.53)$$

$$\text{DiBS} = \{\text{Length} = 15.3 \text{ cm}\} \quad (5.54)$$

$$\text{WeBS} = \{0.07 \text{ gr}\} \quad (5.55)$$

$$\text{NuL} = \{6\} \quad (5.56)$$

$$\text{PaL} = \{\text{front legs}, \text{middle legs}, \text{hind legs}\} \quad (5.57)$$

$$\text{LoL}_{\text{front}} = \text{LoL}_{\text{middle}} = \text{LoL}_{\text{hind}} = \{\text{coxa, femur, tibia, tarsus}\} \quad (5.58)$$

$$\text{FoLb} = \{\text{Fo}_{\text{coxa}}, \text{Fo}_{\text{femur}}, \text{Fo}_{\text{tibia}}, \text{Fo}_{\text{tarsus}}\} \quad (5.59)$$

$$\begin{aligned} \text{JoL}_{\text{front}} &= \text{JoL}_{\text{middle}} = \text{JoL}_{\text{hind}} \\ &= \{\text{body-coxa, coxa-femur, femur-tibia, tibia-tarsus}\} \end{aligned} \quad (5.60)$$

$$\text{ToJo}_{\text{front}} = \{\text{To}_{\text{Fbody-coxa}}, \text{To}_{\text{Fcoxa-femur}}, \text{To}_{\text{FFemur-Tibia}}\} \quad (5.61)$$

$$\text{ToJo}_{\text{middle}} = \text{ToJo}_{\text{hind}} = \{\text{To}_{\text{body-coxa}}, \text{To}_{\text{coxa-femur}}, \text{To}_{\text{Femur-Tibia}}\} \quad (5.62)$$

$$\text{SoM} = \emptyset \quad (5.63)$$

In general, trochanter is neglected because of its small size and passive joint feature [Kram et al., 1997]. Thus, coxa, femur, tibia and tarsus are the limbs of the cockroach (Equation 5.58). In Equation 5.59, *Fo* represents the forms of a limb which are given in Table 5.10. As given in Equation 5.60, the joints of a leg are body-coxa, coxa-femur, femur-tibia and tibia-tarsus. In Equation 5.61 and 5.62, types of joints are abbreviated as *To* which are detailed in Table 5.11 in which tibia-tarsus joint is not given because no information about tibia-tarsus joints is available.

Table 5.10 Forms of limbs of an American cockroach





Limbs	Forms	Max. Dimensions for the American cockroach (cm)
Coxa		Front Leg: 0.14
		Middle Leg: 0.2
		Hind Leg: 0.23
Femur		Front Leg: 0.25
		Middle Leg: 0.34
		Hind Leg: 0.42
Tibia		Front Leg: 0.19
		Middle Leg: 0.31
		Hind Leg: 0.47
Tarsus		Front Leg: 0.23
		Middle Leg: 0.24
		Hind Leg: 0.41

Table 5.11 Cockroach-structures of joints [Kram et al., 1997]

	Body- Coxa	Coxa-Femur	Femur-Tibia
Prothoracic legs (Front legs)	“hinge joint” but coxa can move in sagital plane (y,z)	“hinge joint” with an axis parallel x axis	“hinge joint” with an axis parallel x axis
Mesothoracic legs (Middle legs)	“Proximal joint” with an axis parallel to x axis (1 DOF)	“hinge joint” with an axis parallel to z axis	“hinge joint” with an axis parallel z axis
Metathoracic legs (Hind legs)	“Proximal joint” with an axis parallel to x axis (1 DOF)	“hinge joint” with an axis parallel to z axis	“hinge joint” with an axis parallel to z axis

In Equation 5.52, *FuBS* is function of the biological system. In this case study, climbing locomotion of the American cockroach has been investigated. The classified *FuBS* is given in Equation 5.64.

$$FuBS = \{\text{climbing, joint angles\_climbing}\} \quad (5.64)$$

In Equation 5.64, “joint angles\_climbing” represent joint angles versus time for climbing locomotion type. Joints have been tracked manually with the specified points on the biological system with TEMA Motion® 2D software (Figure 5.17) without painting them. Because of the different structure and active role of the coxa, front legs have been analyzed with four points placed on body-coxa, coxa-femur, femur-tibia and tibia-tarsus joints. Body-coxa joints are not considered for the other legs because of the coxa’s passive character for the middle and hind legs. The joint angles versus time graphs (joint angles\_climbing) for right legs are shown in Figure 5.18.

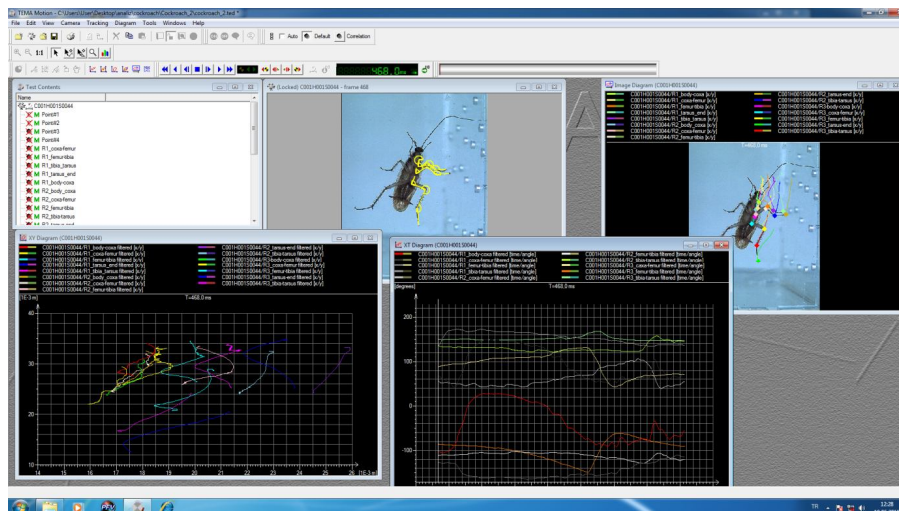


Figure 5.17 A view of cockroach kinematic analysis with TEMA Motion® analysis program

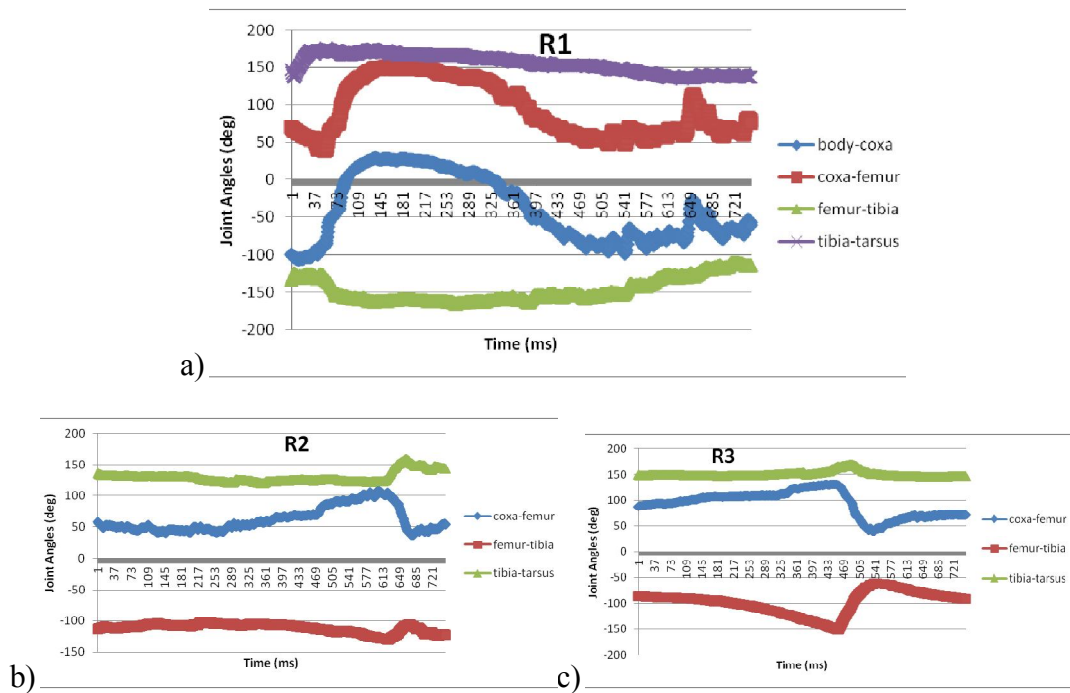


Figure 5.18 Graphs of joint angles versus time for right a) front leg, b) middle leg and c) hind leg.

At the beginning of the experiment, a test set-up for the cockroach climbing has been constructed. In this test set-up, the plexiglass prism has been positioned perpendicular the ground and one end of the prism has been opened. Then, the insect behavior has been observed. For the test scenario, the cockroach;

1. searches environment with its antenna to check whether there is an obstacle and fresh air,
2. searches environment with the left front leg (L1) by touching on the surface to check the suitability of different points of the surface to climb, and
3. changes the position of its legs.

During the experiment, it is observed that the front legs serve as sensors to reach forward, when hind legs generate thrust forces. A cycle of cockroach climbing locomotion is illustrated in Figure 5.19 where R and L shows right and left legs and 1, 2 and 3 symbolize front, middle and hind legs. Stance phases of each leg are represented by black ellipses.

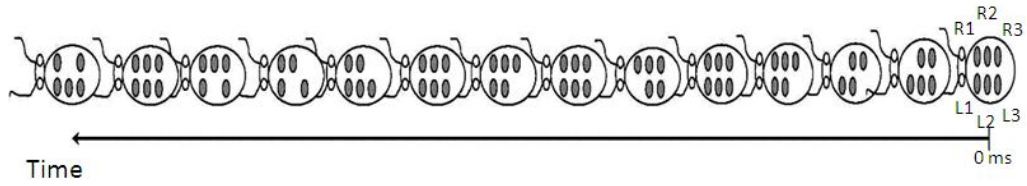


Figure 5.19 A cockroach climbing cycle, including each leg's loop  
(swing-stance phases)

Figure 5.19 shows that swing phases of the legs are followed respectively as R1, L3, L1, L3, R3, L2 and R2. If the first motion of the L3 is ignored, climbing motion is satisfied with the order of front, hind and middle legs motion. Thus, behavior of the American cockroach (BeBS) is represented in Equation 5.65.

$$\begin{aligned} \text{BeBS} &= \{\text{climbing} = \text{no matching for the legs}, \\ &\quad \text{Leg order} = \text{R1, L3, L1, L3, R3, L2, R2}\} \end{aligned} \quad (5.65)$$

#### iv. Bioinspired Transforming ( $S_4$ )

Bioinspired transformation is required to transfer *KBS* (biological domain) to *KBR* (engineering domain). First component of the *KBR* is *MorBR* which is the morphology about the cockroach biorobot (BioCoc) as given in Equation 5.66. Equations 5.67 to 5.70 give several elements of the *MorBR*. *MorBR* is organized during the first sub-state of  $S_4$  (matching) in which forms/structures of the cockroach are matched with known engineering forms/structures. In Equation 5.70, the forms are abbreviated as the *Fo* which are shown in Table 5.12

$$\text{MorBR} = \{\text{NuL, PaL, LoL, FoLb, JoL, ToJo}\} \quad (5.66)$$


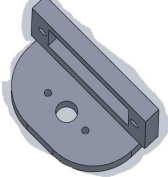

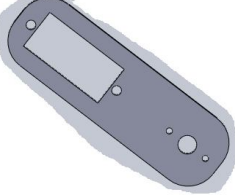

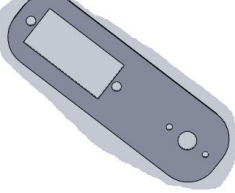

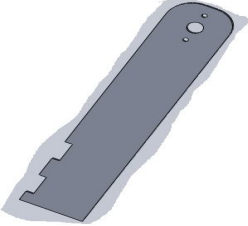
$$\text{NuL} = \{6\} \quad (5.67)$$

$$\text{PaL} = \{\text{front, middle, hind}\} \quad (5.68)$$

$$\text{LoL}_{\text{front}} = \text{LoL}_{\text{middle}} = \text{LoL}_{\text{hind}} = \{\text{coxa, femur, tibia, tarsus}\} \quad (5.69)$$

$$\text{FoLb} = \{\text{Fo}_{\text{coxa}}, \text{Fo}_{\text{femur}}, \text{Fo}_{\text{tibia}}, \text{Fo}_{\text{tarsus}}\} \quad (5.70)$$

Table 5.12 The matched forms and structures of the American cockroach

Limbs	Forms	Matched Engineering Form/Structure	Maximum Dimensions for the biorobot (cm)
Coxa			Front Leg: 7.46
			Middle Leg: 2.4 x 4.0
			Hind Leg: 2.4 x 4.0
Femur			Front Leg: 6.48
			Middle Leg: 10.2
			Hind Leg: 12.6
Tibia			Front Leg: 6.46
			Middle Leg: 9.3
			Hind Leg: 14.1
Tarsus			Front Leg: 6.9
			Middle Leg: 7.2
			Hind Leg: 12.3

For the biorobot, body-coxa joint of front legs move in both x-y and y-z planes as represented Equation 5.71 whereas the body-coxa joints of middle and hind legs move in y-z plane as given Equation 5.72 and shown in Figure 5.16. The other joints (coxa-femur, femur-tibia and tibia-tarsus) are hinge joints (Equation 5.73) and they change position of the cockroach in the x-y plane. Since the joint angles have been collected via video images in the x-y plane only movements are available for analyses. It has been assumed that the motion of each leg in the y-z plane is approximately 60°.

$$\begin{aligned} \text{JoL}_{\text{front}} = \{ & \text{body-coxa (both x-y and y-z plane),} \\ & \text{coxa-femur, femur-tibia, tibia-tarsus} \} \end{aligned} \quad (5.71)$$

$$\begin{aligned} \text{JoL}_{\text{middle}} = \text{JoL}_{\text{hind}} = \{ & \text{body-coxa (y-z plane),} \\ & \text{coxa-femur, femur-tibia, tibia-tarsus} \} \end{aligned} \quad (5.72)$$

$$\text{ToJo} = \{ \text{joints} = \text{hinge joints} \} \quad (5.73)$$

The second sub-state of  $S_4$  is “separating” in which a climbing cycle of the cockroach should be identified. Because of the small time interval of the selected video record, series of the climbing motion cycle (swing-stance phases) have not been observed completely. It is assumed that the selected video record provides a complete climbing locomotion cycle. Thus, data shown in Figure 5.18 is used for joint angles of the cockroach biorobot. In these graphs, it is observed that the initial and the final angles are not the same. This may cause some stability problems for the biorobot when it repeats the locomotion cycle. Thus, in the third sub-state of  $S_4$ ; “modeling” sub-state, switching has been applied between the final and initial angles to close the locomotion cycle smoothly. Thus, Figure 5.18 has been used with small data switching process as a “dynamic model of climbing” for the biorobot (Equation 5.74).

Data of the joint angles have been derived for twenty points to provide symmetry in the fifth sub-state; “synchronizing” sub-state. Hence, “climbing legs combination” given in Equation 5.75 has been used from Figure 5.19.  $I_4$  is the information about the cockroach biorobot and in this case study,  $I_4$  is assumed to be equal to  $KBR$ .

$$\text{FuBR} = \{ \text{climbing, dynamic model of climbing} \} \quad (5.74)$$

$$\text{BeBR} = \{ \text{no matching legs for walking, climbing legs combination} \} \quad (5.75)$$

#### **v. Engineering Structure Generalizing ( $S_5$ )**

Alternative engineering structures for the cockroach climbing biorobot based on the  $KBR$  is listed in Table 5.13. Generated  $ES$  is given in Equation 5.76.

Table 5.13 The Morphological Matrix of the cockroach biorobot (BioCoc)

		Alternatives		
		1	2	3
MorBR	Limbs (Links)	Plexiglass	Aluminum	Steel
	Joints (Hinge joints)	Pin type	x	x
FuBR	Actuator	Servo motors	Pneumatic	Muscle wire
	Controller	Arduino	x	x
BeBR	Controller	Arduino	x	x

$$ES = (\{Plexiglass, Aluminium, Steel\}, Pin\ type, \{Servo\ motors, Pneumatic, Muscle\ wires\}, Arduino) \quad (5.76)$$

#### vi. Engineering Structure Selecting ( $S_6$ )

Table 5.14 gives the concept alternatives for the cockroach biorobot. According to the *ES*, nine concept alternatives for the cockroach biorobot were combined.

Table 5.14 Concept alternatives of the cockroach biorobot

	<b>Material of links</b>	<b>Joint</b>	<b>Actuator</b>	<b>Controller for FuBR</b>	<b>Controller for BeBR</b>
C <sub>1</sub>	Plexiglass	Pin-type	Servo motor	Arduino	Arduino
C <sub>2</sub>	Plexiglass	Pin-type	Pneumatic	Arduino	Arduino
C <sub>3</sub>	Plexiglass	Pin-type	Muscle wire	Arduino	Arduino
C <sub>4</sub>	Aluminum	Pin-type	Servo motor	Arduino	Arduino
C <sub>5</sub>	Aluminum	Pin-type	Pneumatic	Arduino	Arduino
C <sub>6</sub>	Aluminum	Pin-type	Muscle wire	Arduino	Arduino
C <sub>7</sub>	Steel	Pin-type	Servo motor	Arduino	Arduino
C <sub>8</sub>	Steel	Pin-type	Pneumatic	Arduino	Arduino
C <sub>9</sub>	Steel	Pin-type	Muscle wire	Arduino	Arduino

In order to make selection, the following criteria are used based on *Co*.

- High cockroach-like appearance,
- Small size (max. 10 cm<sup>3</sup>),
- Light weight (max. 1 kg).

The concepts' overall ratings are calculated using Weighted Rating Method and they are given in Table 5.15.

Table 5.15 Weighted Rating Method for evaluation criteria of the cockroach biorobot

(Rating: Unsatisfactory = 0, Just tolerable = 1, Adequate = 2, Good = 3, Very good = 4 and NA = not applicable)

Criteria	Concept Alternatives																		
	Importance Weight (%)	C <sub>1</sub>		C <sub>2</sub>		C <sub>3</sub>		C <sub>4</sub>		C <sub>5</sub>		C <sub>6</sub>		C <sub>7</sub>		C <sub>8</sub>		C <sub>9</sub>	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
High cockroach-like appearance	40	4	1.6	4	1.6	4	1.6	2	0.8	2	0.8	2	0.8	2	0.8	2	0.8	2	0.8
Small size	20	3	0.6	3	0.6	4	0.8	2	0.4	2	0.4	3	0.6	2	0.4	2	0.4	3	0.6
Light weight	40	4	1.6	3	1.2	4	1.6	3	1.2	2	0.8	3	1.2	3	1.2	2	0.8	3	1.2
Total	100	NA	3.8	NA	3.4	NA	4.0	NA	2.4	NA	2.0	NA	2.6	NA	2.4	NA	2.0	NA	2.6

Although C<sub>3</sub> has a higher grade, C<sub>1</sub> (with plexiglass, pin-type, servo motors and Arduino) has been selected for the initial preliminary prototype of the cockroach biorobot because of the experience on servo motor controls. The initial prototype was manufactured and it is shown in Figure 5.20. The prototype is approximately 25 times bigger than the cockroach used in the experiment. 26 servo motors have been used for actuation of each limb. Refined joint angles have been loaded on Arduino Mega to control the servo motors; 10 for front legs, 8 for middle legs and 8 for hind legs.

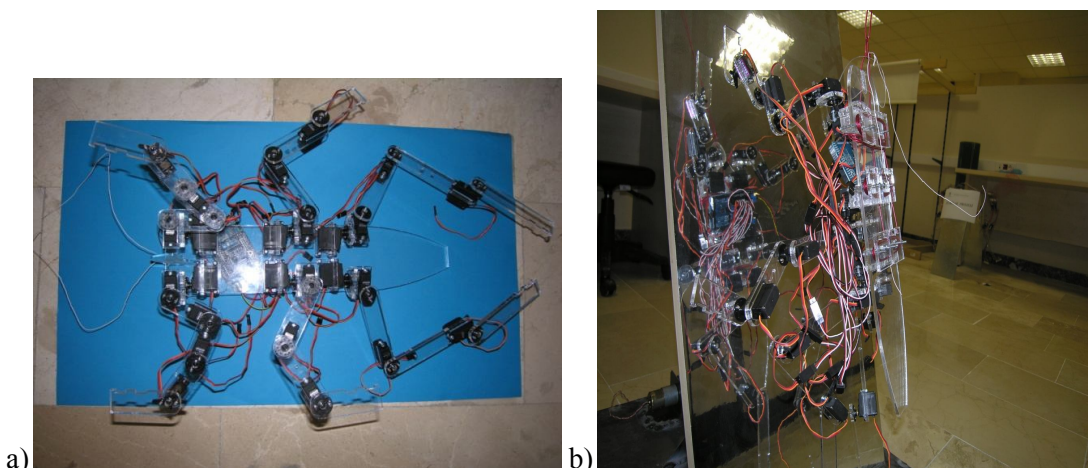


Figure 5.20 A view of a preliminary prototype of the cockroach biorobot a) top view  
b) isometric view

Climbing is based on an attachment mechanism, foot morphology and/or the number of leg [Goldman et al., 2006]. Existing climbing robots have employed various mechanical attachment mechanisms, including suction cups, magnets and claws [Pretto et al., 2008] and synthetic dry fibrillar adhesive which mimics the Gecko adhesive pad structure [Menon and Sitti, 2005]. Similarly, adhesive pads inspired from the cockroach will be used for the desired BioCoc. Since this study focuses on the implementation of the BICD by developing a demonstrative biorobot prototype, main concentration is for the simulation of climbing motion through a real physical system. Thus, design of an attachment mechanism for real climbing is left to future studies. The climbing behavior is pretended with an elevator platform with a constant speed for demonstrative purposes. The preliminary prototype of the cockroach biorobot for climbing motion with an elevator platform is shown in Figure 5.21.



Figure 5.21 A view of the cockroach biorobot with climbing platform

### ***Discussion about the Cockroach Biorobot (BioCoc)***

Design and manufacturing process of cockroach biorobot prototype is based on some assumptions and limitations [Konez Eroğlu et al., 2012], which are classified and discussed below in two main groups.

#### ***Limitations on the Experimental Set-up:***

- The cockroach is not attached on a treadmill, so it climbed freely. Thus, a real linear climbing motion is not observed during the experiment. A video image including a small part of linear motion is used to analyze the locomotion.
- Because of the small time interval of the selected video image, climbing motion loop series (swing-stance phase) are not observed fully. It is assumed that the selected video record provides a loop for complete climbing motion (a cycle).
- Since the cycles of cockroach climbing motion are not observed during the experiment, collected data of joint angles is not switched or smoothed for the case study. Transition angles are applied between the final and initial angles to close the locomotion cycle smoothly.
- Ten joint points for the right side of the cockroach have been tracked and angle-time discrete data sets have been collected using the motion analysis software. To provide symmetry, data of joint angles have been generated for twenty points. Then, information about biological system is transferred to engineering domain by using standard engineering forms/structures.
- The insect used in the experiment is too small for marking/painting. Thus, joints have been tracked hardly in the analysis process.
- During the experiment, two dimensional video images are collected. However, cockroaches climb on both the x-y and the y-z planes. Thus, leg movements in the z-direction are assumed about 60 degrees.

#### ***Limitations on the Material:***

- Sensor information provided by antenna and left front leg was ignored for the study. Only leg motions were considered.
- The biorobot cannot contact with any surface. Because of the material limitations of the attachment mechanisms, the robot only simulates the climbing motion; it is

not able to climb on a surface. Thus, linear motion of the body was implemented with a platform which has a constant linear velocity related the real velocity of the cockroach.

### 5.2.3 Jumping Biorobot

Jumping biorobot is the third case study for the BICD process. It is based on PB and at the end of the design a concept of the biorobot is expected. Initial efforts for this case study were given in [Konez Eroğlu et al., 2011\_b].

For this case study, it is assumed that the customer states “I need an insect robot which can jump on a smooth surface. It looks like the master system and it has maximum 2 cm<sup>3</sup> volume and maximum 2 kg weight. Operational environment temperature varies in between -10°C and 40°C.” The BICD methodology is applied to this design case as follows.

#### i. Task Clarifying

*Fu* and *Co* are classified by using a requirements list based on the customer need. Requirements of the expected biorobot are collected and summarized in Table 5.16 and *Fu* and *Co* are given in Equation from 5.77 to 5.84.

Table 5.16 The requirements list of a jumping biorobot

Main Headings		Requirement List
Type of the Biological System		Insect
Species of the Biological System (if specified)		-
Morphology of the Final Product		master-like appearance Max. 2 kg. Max. 2 cm <sup>3</sup>
Expected Function of the Final Product	Motoric	Jumping
	Sensoric	-
	Cognitive	-
Specified Expected Features		-
Operational Environment		Temp: between -10°C and 40°C Smooth surface
Production and Assembly		Modular
Cost		-
Schedule		-

$$Fu = \{\text{jumping}\} \quad (5.77)$$

$$Co = \{\text{SBS, Mor, Spe, OpE, Cos, Sce}\} \quad (5.78)$$

$$\text{SBS} = \{\text{Insect}\} \quad (5.79)$$

$$\text{Mor} = \{\text{master-like, max. } 2 \text{ cm}^3, \text{ max. } 2 \text{ kg}\} \quad (5.80)$$

$$\text{Spe} = \emptyset \quad (5.81)$$

$$\text{OpE} = \{\text{Temp= between } -10^\circ\text{C and } 40^\circ\text{C, smooth surface}\} \quad (5.82)$$

$$\text{Cos} = \emptyset \quad (5.83)$$

$$\text{Sce} = \emptyset \quad (5.84)$$

## ii. Biological System Selecting

An insect biorobot is expected by the customer. Several examples of jumping insects are listed in Equation 5.85. These are collected from a webpage [Jumping Insects, 2012].

$$I_2 = \{\text{grasshoppers, fleas, praying mantises, katydids, flea beetles, crickets, click beetles}\} \quad (5.85)$$

The designer selects grasshoppers because of the ease of finding information about the grasshoppers in the literature. Pholidoptera has been selected as the breed of grasshoppers because sufficient data are given for this breed in the studies of Burrows and Morris [Burrows and Morris, 2002].

## iii. Biological System Analyzing

The Pholidoptera grasshopper has been analyzed for the jumping function. In this analysis, content analysis method (literature survey) is used to develop KBS of the grasshopper. *MorBS* is the morphology of the grasshopper and it is given in Equation 5.86. The related literature [Burrows and Morris, 2002; Heitler, 2005] shows that grasshoppers jump by using their hind legs powered with flexor and tensor muscles as well as the storing energy in a special cuticle.

$$\text{MorBS} = \{\text{DiBS}, \text{WeBS}, \text{NuL}, \text{PaL}, \text{LoL}, \text{FoLb}, \text{JoL}, \text{ToJo}, \text{SoM}\} \quad (5.86)$$

In Equation 5.87, *DiBS* represent the dimensions of the grasshopper. Dimensions of the grasshoppers' hind leg which performs the jumping are given in Table 5.17. The total weight of the grasshopper is given in Equation 5.88.

$$\text{DiBS} = \emptyset \quad (5.87)$$

$$\text{WeBS} = \{415 \text{ mg}\} \quad (5.88)$$

Table 5.17 Average dimensions and weight of the grasshopper [Burrows et al., 2002]

Body Structure	Total body mass (M)	415 mg
	Hind leg tibia length ( $L_{\text{tibia}}$ )	15.6 mm
	Hind leg femur length ( $L_{\text{femur}}$ )	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	4.4 mm <sup>2</sup>
	Flexor muscle occupying a cross-sectional area	1.08 mm <sup>2</sup>
	Angle of rotation of tibia	165°

Figure 5.22 shows that grasshoppers have three pair of legs (Equation 5.89). These are front, middle and hind legs as represented in Equation 5.90. As shown in Figure 5.22, the hind (jumping) leg and the others have five distinct segments; coxa, trochanter, femur, tibia and tarsus. However, as given in Equation 5.91 four limbs are considered. Because of the passive structure of the trochanter, this structure can be neglected.

$$\text{NuL} = \{6\} \quad (5.89)$$

$$\text{PaL} = \{\text{front legs}, \text{middle legs}, \text{hind legs}\} \quad (5.90)$$

$$\text{LoL}_{\text{front}} = \text{LoL}_{\text{middle}} = \text{LoL}_{\text{hind}} = \{\text{coxa}, \text{femur}, \text{tibia}, \text{tarsus}\} \quad (5.91)$$

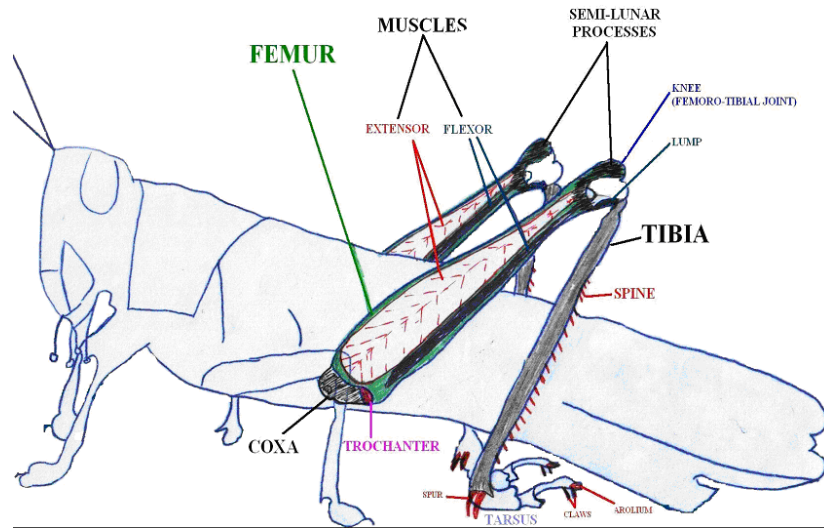


Figure 5.22 Limbs and joints of the grasshopper hind (jumping) leg [Konez Eroğlu, 2007]

Equation 5.92 gives the forms of the limbs of grasshopper leg which are illustrated in Figure 5.22. The joints are represented in Equation 5.93. As given in Equation 5.94, the joints are hinge joints. The joint knee has a special structure because at the knee, there is a special cuticle (semi-lunar process) which stores most of the jumping energy. As represented in Equation 5.95, during the jumping, grasshoppers use flexor and extensor muscles.

$$FoL_{b_{hind}} = \{Fo_{coxa}, Fo_{femur}, Fo_{tibia}, Fo_{tarsus}\} \quad (5.92)$$

$$JoL_{front} = \{body-coxa, coxa-femur, knee, tibia-tarsus\} \quad (5.93)$$

$$ToJo = \{joints = hinge joints, knee has a special cuticle\} \quad (5.94)$$

$$SoM = \{flexor, extensor\} \quad (5.95)$$

$FuBS$  is the function of the grasshopper and is given in Equation 5.96. In the equation, “knee angle versus time” is given in Figure 5.23.

$$FuBS = \{jumping = 1.79 \text{ m/s (take-off velocity), knee angle versus time}\} \quad (5.96)$$

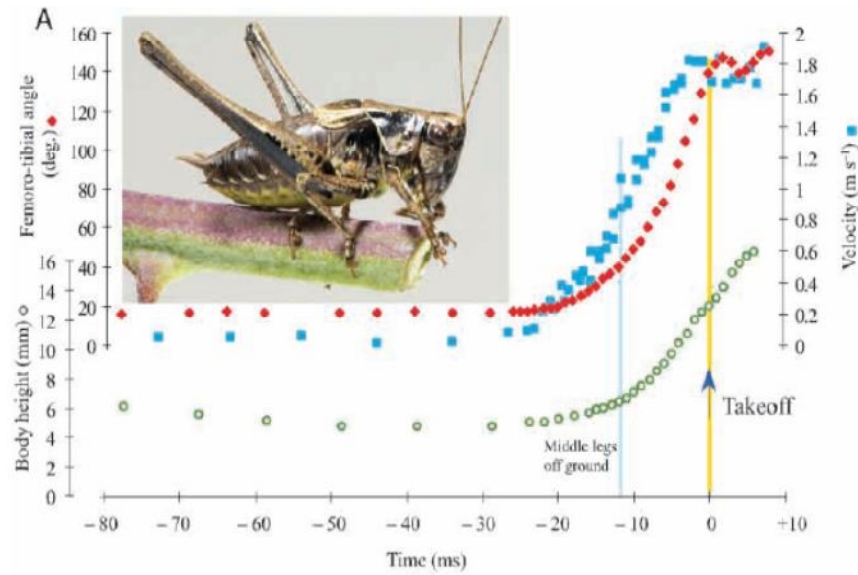


Figure 5.23 The changes in the Femur-Tibia angle, body height and velocity of body movement during a jump by a Pholidoptera male [Burrows and Morris, 2002].

*BeBS* is the behavior of the grasshopper and it is represented in Equation 5.97. According to Burrows and Morris [Burrows and Morris, 2002], jumping of a grasshopper has a routine program as illustrated in Figure 5.24 and

1. 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. The flexion of the tibia is not always complete so that one or both hind legs could begin their rapid extension movement from the partially extended position.
2. As the hind tibiae are extended, the body is raised from the ground and the forwardly directed antennae are swung backwards to point over the body.
3. When viewed from the front side, the hind legs can be seen to rotate outwards at their joints with the coxa, and both the middle and front legs depress at their coxa joints and extend at their femur-tibia joints.
4. The continuing elevation of the body eventually leads to the front and middle legs losing contact with the ground before the hind legs, so that it is the hind legs that provide the thrust for the final 10-12 ms before the insect becomes airborne.

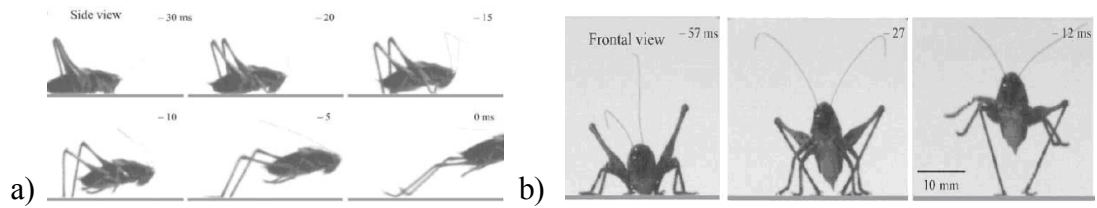


Figure 5.24 Selected frames from the same jump a) Viewed from the side, b) Viewed head-on [Burrows and Morris, 2002].

$$\text{BeBS} = \{\text{jumping} = \text{by hind legs, body elevation} = \text{by front and middle legs, jumping steps} = \text{initial flexion, body elevation, rotation about the body-coxa joint}\} \quad (5.97)$$

#### iv. Bioinspired Transforming

In this state, KBS is transformed to KBR by following the sub-states “matching”, “separating”, “modeling” and “synchronizing”, respectively. In this case study, coxa and tarsus have been ignored to reduce complexity of the model. Thus, the cockroach biorobot is designed with 2 limbs (femur and tibia) instead of 5 limbs in the actual model and the model of the biorobot has 3 degrees of freedom (DOF). Femur and tibia are matched with cylindrical prisms and their dimensions are  $L_1=17.1$  mm and  $L_2= 15.6$  mm (Table 5.17).

There are three angles: femur- tibia angle (knee,  $\alpha(t)$ ) and body-femur angles ( $\beta(t)$  and  $\gamma(t)$ ) for the two limbs as shown in Figure 5.25, two hinge joints: body-femur and femur-tibia are modeled. To prevent complexity of the robot and reducing the number of degrees of freedom to a manageable level the rear legs also froze the active  $\gamma(t)$  joint at  $30^\circ$ .

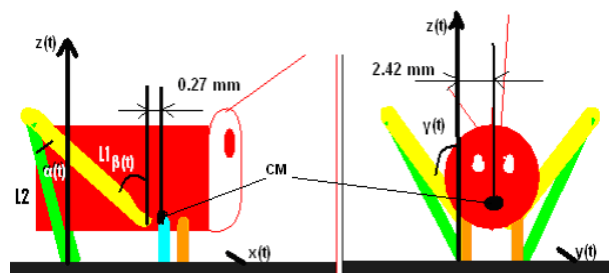


Figure 5.25 The grasshopper (Pholidoptera) leg model (CM: Centre of Mass) [Konez Eroglu et al., 2006; Konez Eroglu, 2007; Konez Eroglu et al., 2008]

Body height ( $z(t)$ ) and femur-tibia angle ( $\alpha(t)$ ) changes are assumed to be zero in the interval between -80 ms to -20 ms. The  $z(t)$  and  $\alpha(t)$  are represented analytically by using the empirical data obtained from the Figure 5.23 where -20 ms are shifted to origin for using positive time in equations (Figure 5.26).  $z(t)$  and  $\alpha(t)$  are given in Equation 5.98 and Equation 5.99 where units of  $z(t)$  and  $\alpha(t)$  are “mm” and “deg”  $\beta(t)$  are given in Equations from 5.100 to 5.104 which were calculated by Konez Eroğlu [Konez Eroğlu et al., 2006; Konez Eroğlu, 2007; Konez Eroğlu et al., 2008]. The body velocity during taking-off is given in Equation 5.105. Variations of angles  $\alpha(t)$ ,  $\gamma(t)$  and  $\beta(t)$  are given in the Figure 5.27 and the body velocity is plotted in the Figure 5.28.

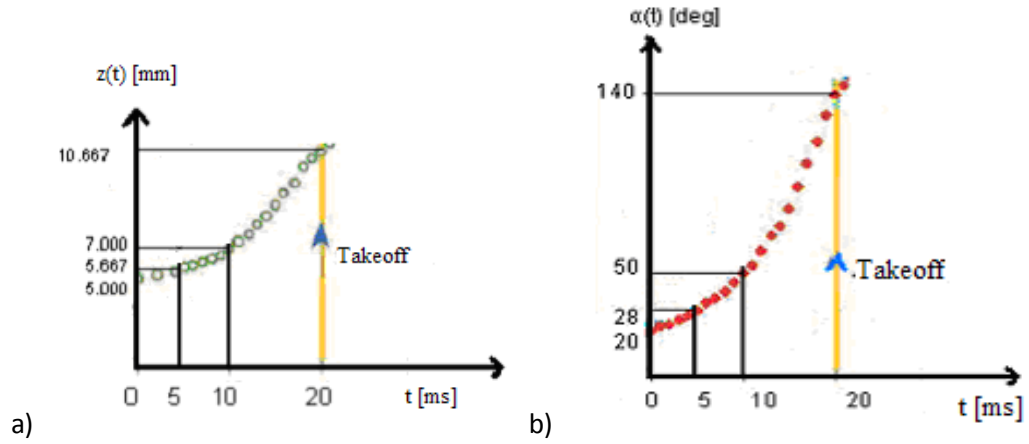


Figure 5.26 For positive time definite, a) Body height ( $z(t)$ ) and b) Femur-Tibia angle ( $\alpha(t)$ ) of the Pholidoptera grasshopper before take-off [Konez Eroğlu, 2007]

$$z(t) = -0.00332333t^3 + 0.018305t^2 + 0.0501833t + 5 \quad (5.98)$$

$$\alpha(t) = 0.00133333t^3 + 0.026t^2 + 0.26666675t + 20 \quad (5.99)$$

$$\beta(t) = \delta(t) + \arccos\left(\frac{z(t)}{E(t)}\right) \quad (5.100)$$

$$E(t) = \sqrt{(C + D \cdot \cos(\alpha(t)))^2 + (D \cdot \sin(\alpha(t)))^2} \quad (5.101)$$

$$\delta(t) = \arctan\left(\frac{D \cdot \sin(\alpha(t))}{C + D \cdot \cos(\alpha(t))}\right) \quad (5.102)$$

$$C = -L1. \cos (\gamma(t)) \quad (5.103)$$

$$D = L2. \cos (\gamma(t)) \quad (5.104)$$

$$V(t) = \left( \left( \frac{dx(t)}{dt} \right)^2 + \left( \frac{dz(t)}{dt} \right)^2 \right)^{1/2} \quad (5.105)$$

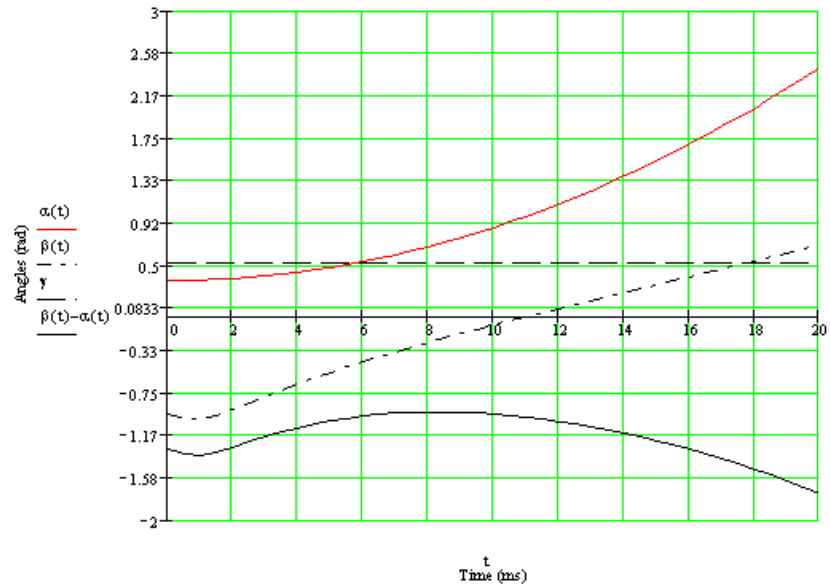


Figure 5.27 Variations of Femur-Tibia ( $\alpha(t)$ ), Body-Femur ( $\beta(t)$  and  $\gamma(t)$ ), and Ground-Tibia ( $\beta(t) - \alpha(t)$ ) angles until take-off [Konez Eroğlu, 2007]

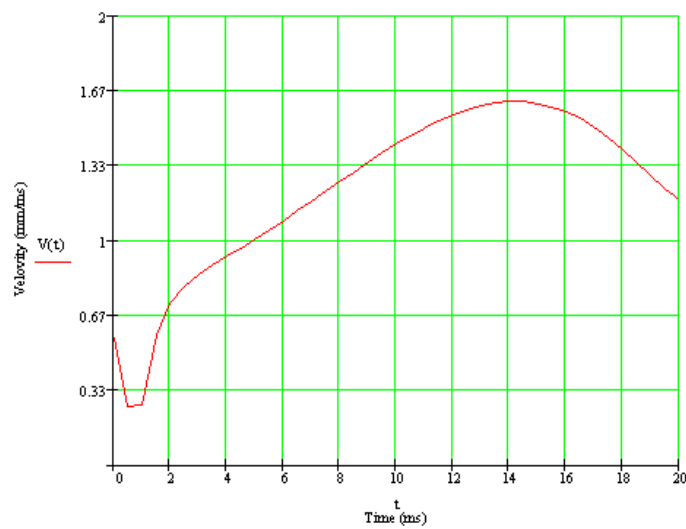


Figure 5.28 A plot of velocity until take-off [Konez Eroğlu, 2007]

Knowledge about the jumping (grasshopper) biorobot (KBR) is achieved and organized in Equations 5.106 to 5.115. As represented in Equation 5.114, “dynamic model of jumping” was given in Equations 5.98 to 5.105 and illustrated in Figure 5.27 and Figure 5.28.  $I_4$  is the information about the jumping (grasshopper) biorobot and in this case study,  $I_4$  is assumed to be equal to  $KBR$ .

$$\text{MorBR} = \{\text{NuL}, \text{PaL}, \text{LoL}, \text{FoLb}, \text{JoL}, \text{ToJo}\} \quad (5.106)$$

$$\text{NuL} = \{6\} \quad (5.107)$$

$$\text{PaL} = \{\text{front}, \text{middle}, \text{hind}\} \quad (5.108)$$

$$\text{LoL}_{\text{front}} = \text{LoL}_{\text{front}} = \{\text{femur}\} \quad (5.109)$$

$$\text{LoL}_{\text{hind}} = \{\text{femur}, \text{tibia}\} \quad (5.110)$$

$$\text{FoLb} = \{\text{limbs} = \text{cylindrical prisms}\} \quad (5.111)$$

$$\text{JoL} = \{\text{femur- tibia angle } (\alpha(t)) \text{ and body-femur angles } (\gamma(t) \text{ and } \beta(t))\} \quad (5.112)$$

$$\begin{aligned} \text{ToJo} = \{ & \gamma(t) = \text{fixed}, \alpha(t) \text{ and } \beta(t) = \text{hinge joints}, \\ & \text{at knee} = \text{a structure for energy storing} \} \end{aligned} \quad (5.113)$$

$$\text{FuBR} = \{\text{jumping}, \text{dynamic model of jumping}\} \quad (5.114)$$

$$\begin{aligned} \text{BeBR} = \{ & \text{jumping} = \text{hind legs}, \text{body elevation} = \text{front and middle legs}, \\ & \text{jumping steps} = \text{initial flexion}, \text{body elevation}, \\ & \text{rotation about the body-coxa joint} \} \end{aligned} \quad (5.115)$$

In this step, KBS is transformed to KBR in engineering domain. In step five, this knowledge is used to generate engineering structures.

#### v. Engineering Structures Generalizing

The engineering structures (ES) for the jumping biorobot are generated in this stage based on  $Fu$ ,  $Co$  and  $KBR$ . Table 5.18 provides a list of structure examples.

Table 5.18 The Morphological Matrix of the jumping (grasshopper) biorobot

		Alternatives		
		1	2	3
MorBR	Limbs (Links)	Steel	x	x
	Joints (Hinge joints)	Pin type	x	x
	The storing energy element at the knee (the special cuticle)	Torsional Spring	Flywheel	x
FuBR	Actuator	Servo motors	EAP	Pneumatic
	Controller	Arduino	x	x
BeBR	Controller	Arduino	x	x

In this step, ES has been obtained. In the next step, concept alternatives are generated by using the ES and a design concept is selected for the jumping biorobot.

#### vi. Engineering Structures Selecting

Concept alternatives of the biorobot based on the *ES* are tabulated in Table 5.19.

Table 5.19 Concept alternatives of the jumping (grasshopper) biorobot

	Material of links	Joint	Storing Energy	Actuator	Controller for FuBR	Controller for BeBR
C <sub>1</sub>	Steel	Pin-type	Torsional spring	Servo motor	Arduino	Arduino
C <sub>2</sub>	Steel	Pin-type	Torsional spring	EAP	Arduino	Arduino
C <sub>3</sub>	Steel	Pin-type	Torsional spring	Pneumatic	Arduino	Arduino
C <sub>4</sub>	Steel	Pin-type	Flywheel	Servo motor	Arduino	Arduino
C <sub>5</sub>	Steel	Pin-type	Flywheel	EAP	Arduino	Arduino
C <sub>6</sub>	Steel	Pin-type	Flywheel	Pneumatic	Arduino	Arduino

An appropriate concept has been selected by using Weighted Rating Method. The evaluation criteria are derived from the *Co* and selected as follows:

- High master (grasshopper)-like appearance,
- Small size (max. 2 cm<sup>3</sup>),
- Light weight (max. 2 kg),
- Operational environment (-10 °C ≤ T ≤ 40 °C).

The concepts' ratings based on weights of the criteria are given in Table 5.20.

Table 5.20 Weighted Rating Method for evaluation criteria of the jumping (grasshopper) biorobot

(Rating: Unsatisfactory = 0, Just tolerable = 1, Adequate = 2, Good = 3, Very good = 4 and NA = not applicable)

Criteria	Importance Weight (%)	Concept Variants											
		C <sub>1</sub>		C <sub>2</sub>		C <sub>3</sub>		C <sub>4</sub>		C <sub>5</sub>		C <sub>6</sub>	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
High master-like appearance	40	3	1.2	4	1.6	3	1.2	2	0.8	3	1.2	2	0.8
Small size	20	3	0.6	4	0.8	2	0.4	2	0.4	3	0.6	1	0.2
Light weight	20	3	0.6	3	0.6	2	0.4	2	0.4	3	0.6	1	0.2
Operational environment	20	2	0.4	2	0.4	2	0.4	2	0.4	2	0.4	2	0.4
Total	100	NA	2.8	NA	3.4	NA	2.4	NA	2.0	NA	2.8	NA	1.6

As seen in Table 5.20, C<sub>2</sub> has higher grade. The selected combination (C<sub>2</sub>) gives the conceptual design of the jumping (grasshopper) biorobot. This concept includes steel material for limbs, pin-type hinge joints, torsion spring, EAP actuators and Arduino controller. A demonstrative leg prototype was designed and manufactured with delrin material without using any actuator or controller. The prototype is shown in Figure 5.29.

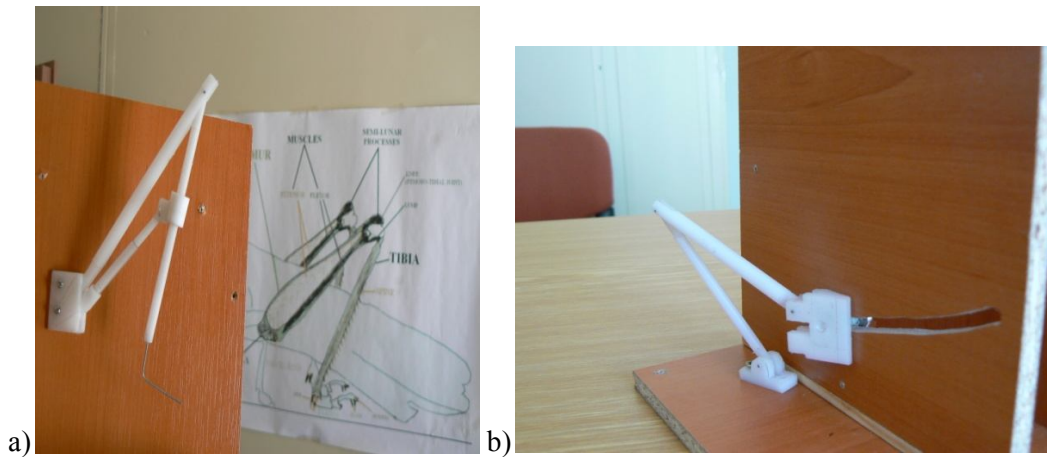


Figure 5.29 Views of a) the grasshopper jumping leg prototype b) position of center of mass prototype in a jumping leg model until take-off

#### 5.2.4 Hybrid Biorobot

This case study is an example for the implementation of the BICD methodology on hybrid biorobots which have different morphology, functions and behaviors derived from multiple biological systems.

In this case, it is assumed that a walking robot is desired by a customer. The biorobot should walk on an indoor smooth surface and also on the seafloor. The seafloor is in a stream environment with slow currents. In the scenario, the customer wants Arduino platform to control the robot and an animal-like appearance.

Biological system(s) is not clear in this problem, so it is a case study of the PB-BICD approach. The BICD methodology is applied as explained below.

##### i. Task Clarifying

A walking biorobot is desired as the final product. According to the scenario, this robot walks on an indoor smooth surface and also moves in a stream environment with slow currents (underwater or seafloor walking). Information about sensors or cognition of the biorobot is not provided by the customer. To simplify the design, it is assumed that walking modes can be changed manually by the customer. In this case study, the customer prefers an Arduino platform to control the biorobot. In addition, the biorobot should have an animal-like appearance. A requirements list of the desired product is given in Table 5.21 in which *Fu* has two main functions and

these are given in Equation 5.116.  $Co$  of the case study is given in Equations from 5.117 to 5.123.

Table 5.21 The requirements list of the biorobot

Main Headings		Requirement List
Type of Biological System		Animal
Species of the Biological System (if specified)		-
Morphology of the final product		Animal-like, max. 10 cm <sup>3</sup>
Expected Function of the Final Product	Motoric	Walking (smooth surface and seafloor)
	Sensory	-
	Cognitive	-
Specified Expected Features		Arduino
Operational Environment		Indoor smooth surface and stream environment with slow currents
Cost		-
Schedule		-

$$Fu = \{\text{walking on an indoor smooth surface, walking on seafloor}\} \quad (5.116)$$

$$Co = \{SBS, Mor, Spe, OpE, Cos, Sce\} \quad (5.117)$$

$$SBS = \emptyset \quad (5.118)$$

$$Mor = \{App, Siz, Weh, Heh, NuL\} = \{\text{animal-like}\} \quad (5.119)$$

$$Spe = \{\text{Arduino}\} \quad (5.120)$$

$$OpE = \{\text{Indoor smooth surface and stream environment with slow currents}\} \quad (5.121)$$

$$Cos = \emptyset \quad (5.122)$$

$$Sce = \emptyset \quad (5.123)$$

The other steps of the BICD design are based on the  $Fu$  and  $Co$ . In the next state, biological system or systems are selected according to the  $Fu$  and  $Co$ .

## ii. Biological System Selecting

Research on the Internet gives many alternatives for sub-functions of “walking on an indoor smooth surface” and “walking on seafloor” For the first sub-function, several

alternatives are collected in Equation 5.124. Equation 5.125 gives a biological system which can walk on seafloor.

$$I_{2\text{land}} = (\text{human, flamingo, dog, cat, cow, camel,} \\ \text{grasshopper, spider, cockroach, lobster}) \quad (5.124)$$

$$I_{2\text{seafloor}} = \{\text{lobster and so on}\} \quad (5.125)$$

In this case study, depending on previous experiences and existing test data, a (Terrier) dog walking is selected to perform the sub-function of walking on an indoor smooth surface. In addition, an American lobster is selected for the second sub-function, walk on seafloor. Therefore, a Terrier dog and an American lobster are chosen for walking locomotion on an indoor smooth surface and seafloor as represented in Equation 5.126. Thus, biorobot will be designed as *a hybrid biorobot* which combines walking behaviors of a dog and a lobster.

$$\text{BrBS} = \{\text{Terrier dog, American lobster}\} \quad (5.126)$$

### iii. Biological System Analyzing

In this case study, the designer selects the observation method to analyze the dog and literature survey method to analyze the lobster.

#### a. Analysis of the Dog

The dog was analyzed in the first case study and knowledge about the dog for walking and trotting was given in Section 5.2.1. Required walking knowledge for this case study is given for this case study in this section. *MorBS* of the dog is same with Equation 5.13. *FuBS* of the dog for this case study is given in Equation 5.127 where “joint angles\_walking” represents the joint angles obtained when the dog walks and was displayed in Figure 5.5. *BeBS* of the dog is represented in Equation 5.128 and “walking legs combination” was illustrated in Figure 5.7.

$$\text{FuBS} = \{\text{walking} = 1 \text{ km/h, joint angles\_walking}\} \quad (5.127)$$

$$\text{BeBS} = \{\text{walking} = \text{no matching for legs, walking legs combination}\} \quad (5.128)$$

### b. Analysis of the Lobster

An American lobster, which is shown in Figure 5.30, is selected to perform the function of walking on seafloor. *MorBS* is the morphology of the lobster and is represented in Equations 5.129. Required data for the *MorBS* was collected from the studies of Ayers and his colleagues [Ayers and Davis, 1977; Evoy and Ayers, 1981; Ayers, 2004]. As shown in Equation 5.130 and Equation 5.131, it is assumed that data about the dimensions and the weight of the lobster are not considered for this case study.



Figure 5.30 An American lobster [Lunch, 2012]

$$\text{MorBS} = \{\text{DiBS, WeBS, NuL, PaL, LoL, FoLb, JoL, ToJo, SoM}\} \quad (5.129)$$

$$\text{DiBS} = \emptyset \quad (5.130)$$

$$\text{WeBS} = \emptyset \quad (5.131)$$

Lobsters have eight walking legs (Equation 5.132) and all of them have similar structure (Equation 5.133). The limbs of legs are coxopodite (coxo), basi-schiopodite (basal), meropodite (mero), carpopodite, propodite and dacylopodite as shown in Figure 5.31 and given in Equation 5.134. In Equation 5.135, the limbs forms are represented with *Fo* and the forms can be also seen in Figure 5.31. Although joints of the lobster are T-C (thorax-coxopodite), C-B (coxopodite-basi

ischiopodite), I-M (basi ischiopodite-meropodite), M-C (meropodite-carpopodite), C-P (carpopodite-propodite) and P-D (propodite-dactylopodite), according to Ayers [Ayers, 2004], thoraco-coxal (T-C), coxo-basal (C-B), and mero-carpopodite (M-C) are three major limb joints (Equation 5.136) and they affect lobster walking locomotion. As shown in Equation 5.137 and Equation 5.138, types of joints and muscle structures were not considered in this case study.

$$\text{NuL} = \{8 \text{ (walking leg)}\} \quad (5.132)$$

$$\text{PaL} = \{\text{four walking leg pairs}\} \quad (5.133)$$

$$\text{LoL} = \{\text{coxopodite, basi-ischiopodite, meropodite,} \\ \text{carpopodite, propodite, dactylopodite}\} \quad (5.134)$$

$$\text{FoLb} = \{\text{Fo}_{\text{coxa}}, \text{Fo}_{\text{basal}}, \text{Fo}_{\text{mero}}, \text{Fo}_{\text{carpopodite}}, \text{Fo}_{\text{propodite}}, \text{Fo}_{\text{dactylopodite}}\} \quad (5.135)$$

$$\text{JoL} = \{\text{T-C, C-B, M-C}\} \quad (5.136)$$

$$\text{ToJo} = \emptyset \quad (5.137)$$

$$\text{SoM} = \emptyset \quad (5.138)$$

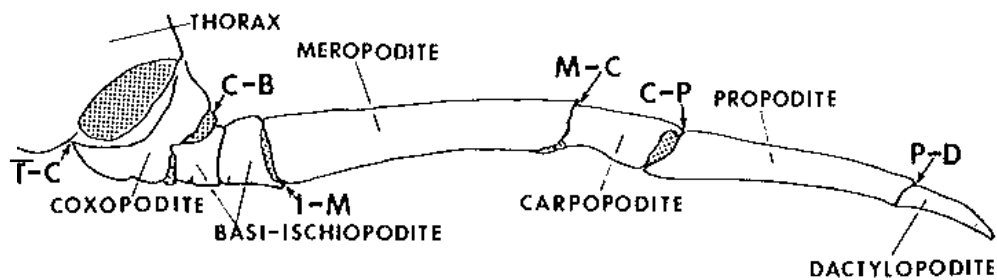


Figure 5.31 Limbs of an American lobster's walking [Evoy and Ayers, 1981]

The function of a lobster was abbreviated as *FuBS* and given in Equation 5.139. Ayers [Ayers, 2004] stated that the movements of the C-B and M-C joints occur in the same plane while movements of the T-C joint occur in a plane at right angles to the others. In addition, he added that a lobster has three phases when it walks [Ayers, 2004];

- an early swing phase: it lifts the limb tip toward the initial position of the stance,
- an early stance phase: it drops the leg to initiate the stance and
- an late stance phase: its limb applies propulsive force and compensates for gravity.

In Equation 5.139, joint angles are shown in Figure 5.32 which represents joint angles versus the mentioned phases of a lobster walking cycle. *BeBS* of the lobster is summarized in Equation 5.140 where walking phases are represented above.

$$\text{FuBS} = \{\text{walking, joint angles}\} \quad (5.139)$$

$$\text{BeBS} = \{\text{walking, walking phases}\} \quad (5.140)$$

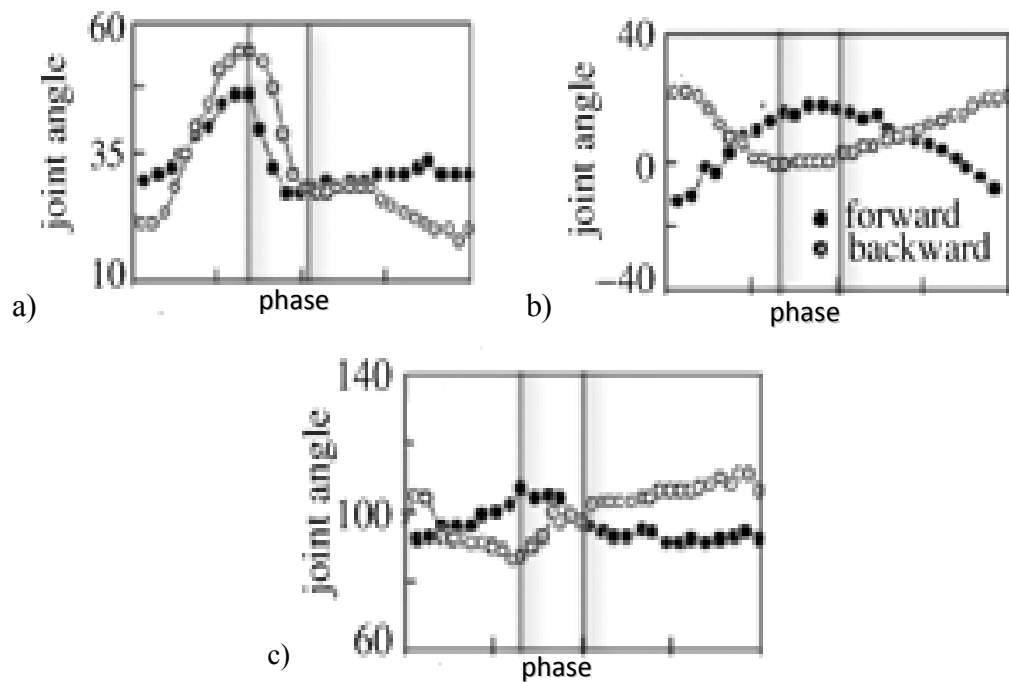


Figure 5.32 The angles of a) coxo-basal (C-B) b) thoraco-coxal (T-C) c) mero-carpopodite (M-C) joints plotted versus phase in the step cycle [Ayers, 2004]

#### iv. Bioinspired Transforming

In this state, morphology, function and behavior about the dog and the lobster are merged and transformed into engineering domain. *MorBR* of the hybrid biorobot is shown in Equation 5.141.

$$\text{MorBR} = \{\text{NuL}, \text{PaL}, \text{LoL}, \text{FoLb}, \text{JoL}, \text{ToJo}\} \quad (5.141)$$

In Equation 5.141, *NuL* is the number of legs. In this case study, the selection of the *NuL* is difficult because lobsters and dogs have different number of legs; dogs have 4 legs while lobsters use 8 legs when they walk. This difference brings two different design alternatives.

The first design alternative is based on the use of original number of legs for each mode. In this alternative, the desired product will be designed with 8 legs like a lobster and the biorobot can be used these all legs when walks on seafloor. Then, when the customer changes the walking mode of the biorobot, the robot will reduce the number of legs by folding four legs. Hence, the biorobot resembles the dog walking behavior with four legs for the indoor smooth surface.

The second design alternative is based on the use of all legs without reducing the number of legs. In this alternative, the biorobot will be designed with 8 legs and all the legs will be used for the two walking modes. When the underwater walking mode is changed to smooth surface walking mode, the dog proceeds to use 8 legs. In this case, first and second legs and third and fourth legs will be paired. Thus, the biorobot shows dog walking behavior as if it would use 4 legs while actually 8 legs will be active.

In this case study, the second design alternative is preferred. Hence, as shown in Equation 5.142, the *NuL* is eight. For the dog walking mode, leg pairs are first-second and third-fourth legs (Equation 5.143) while for the lobster walking mode, the pairs are walking legs (Equation 5.144).

$$\text{NuL} = \{8\} \quad (5.142)$$

$$\text{PaL}_{\text{dog-mode}} = \{\text{first-second, third-fourth}\} \quad (5.143)$$

$$\text{PaL}_{\text{lobster-mode}} = \{\text{walking legs}\} \quad (5.144)$$

As given in Equation 5.145, limbs of the biorobot's legs are femur, tibia and paw. All limbs were matched with rectangular prisms, so in Equation 5.146,  $Fo$  refers to the shape of a rectangular prism. Body-femur, femur-tibia, tibia-paw are three joints of the legs (Equation 5.147) and the joints were modeled as hinge joints shown in Equation 5.148.

$$\begin{aligned} \text{LoL}_{\text{front}} = \text{LoL}_{\text{middle1}} = \text{LoL}_{\text{middle2}} = \text{LoL}_{\text{hind}} \\ = \{\text{femur (meropodite), tibia (carpopodite + propodite), paw}\} \end{aligned} \quad (5.145)$$

$$\text{FoLb} = \{\text{Fo}_{\text{femur}}, \text{Fo}_{\text{tibia}}, \text{Fo}_{\text{paw}}\} \quad (5.146)$$

$$\text{JoL} = \{\text{body-femur, femur-tibia, tibia-paw}\} \quad (5.147)$$

$$\text{ToJo} = \{\text{joints} = \text{hinge joints}\} \quad (5.148)$$

Functions and behaviors of the biological systems are also transformed into  $FuBR$  and  $BeBR$ . These are given in Equation 5.149 and Equation 5.150. In Equation 5.149, “dynamic model of walking\_dog” represents the variation of the dog's joint angles during a walking cycle and it was displayed in Figure 5.9. Similarly, “dynamic model of walking\_lobster” is the variation of the lobster's joint angles during a walking cycle and it was displayed in Figure 5.32. In Equation 5.150, “walking legs combination of dog” was given in Figure 5.11 and “walking legs combination of lobster” was explained in the biological systems analysis step of this case study.

$$\begin{aligned} \text{FuBR} = \{\text{walking\_dog, walking\_lobster,} \\ \text{dynamic model of walking\_dog,} \\ \text{dynamic model of walking\_lobster}\} \end{aligned} \quad (5.149)$$

$$\text{BeBR} = \{\text{dog walking} = 4 \text{ leg mode, lobster walking} = 8 \text{ leg mode,} \\ \text{walking legs combination of dog,} \\ \text{walking legs combination of lobster}\} \quad (5.150)$$

### v. Engineering Structure Generalizing

Several engineering structure alternatives for the hybrid biorobot are listed in Table 5.22.

Table 5.22 The Morphological Matrix of the hybrid biorobot

		Alternatives		
		1	2	3
MorBR	Limbs (Links)	Plexiglass	Polypropylene	x
	Joints (Hinge joints)	Pin type	x	x
FuBR	Actuator	Servo motors	EAP	Pneumatic
	Controller	Arduino	x	x
BeBR	Controller	Arduino	x	x

### vi. Engineering Structure Selecting

Concept alternatives of hybrid biorobot are generated and they are given in Table 5.23.

Table 5.23 Concept alternatives of the hybrid biorobot

	Material of links	Joint	Actuator	Controller for FuBR	Controller for BeBR
C <sub>1</sub>	Plexiglass	Pin-type	Servo motor	Arduino	Arduino
C <sub>2</sub>	Plexiglass	Pin-type	EAP	Arduino	Arduino
C <sub>3</sub>	Plexiglass	Pin-type	Pneumatic	Arduino	Arduino
C <sub>4</sub>	Polypropylene	Pin-type	Servo motor	Arduino	Arduino
C <sub>5</sub>	Polypropylene	Pin-type	EAP	Arduino	Arduino
C <sub>6</sub>	Polypropylene	Pin-type	Pneumatic	Arduino	Arduino

An appropriate concept is selected by using the following evaluation criteria.

- High animal-like appearance,
- Size (max. 10 cm<sup>3</sup>),
- Water resistance.

The comparison of the concepts is given in Table 5.24.

Table 5.24 Weighted Rating Method for evaluation criteria of the hybrid biorobot

(Rating: Unsatisfactory = 0, Just tolerable = 1, Adequate = 2, Good = 3, Very good = 4 and NA = not applicable)

Criteria	Importance Weight (%)	Concept Variants											
		C <sub>1</sub>		C <sub>2</sub>		C <sub>3</sub>		C <sub>4</sub>		C <sub>5</sub>		C <sub>6</sub>	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Animal-like appearance	30	2	0.60	4	1.20	3	0.90	2	0.60	4	1.20	3	0.90
Size	35	2	0.70	4	1.40	3	1.05	2	0.70	4	1.40	3	1.05
Water resistance	35	1	0.35	3	1.05	2	0.70	2	0.70	4	1.40	3	1.05
Total	100	NA	1.65	NA	3.65	NA	2.65	NA	2.0	NA	4.00	NA	3

As seen in Table 5.24, all the evaluation criteria are achieved by C<sub>5</sub>. The selected combination (C<sub>5</sub>) gives the conceptual design of the hybrid biorobot. This concept includes Polypropylene material for limbs, pin-type hinge joints, EAP actuators and Arduino controller. Hybrid biorobot case study is studied at the conceptual design level and therefore a physical prototype is not produced for such a robot.

### 5.3 CHAPTER SUMMARY

In Chapter 5, case studies of the BICD process are presented. During the thesis studies, fourteen biological systems have been investigated and four of them have been studied as the case studies. These case studies are dog biorobot (BioDog), cockroach biorobot (BioCoc), jumping (grasshopper) biorobot and hybrid (walking) biorobot. For the BioDog and BioCoc, prototypes have been produced to demonstrate the implementation of the BICD process. Jumping and hybrid biorobots are only considered at the conceptual design level. Chapter 6 includes detailed discussion on this research and suggestions for future work.

## **CHAPTER 6**

### **DISCUSSION, CONCLUSION AND FUTURE WORK**

The aim of this thesis is to develop a BICD methodology which can be used for systematic design of biorobots. In this chapter, the thesis studies are discussed and summarized. In addition, conclusions and suggestions for future work are given in this chapter.

#### **6.1 DISCUSSION AND CONCLUSION**

Sartori [2010] explained that if engineers had better access to existing biological knowledge, the engineering problems would be easier to solve. Hence, the required knowledge about the biological systems should be well defined and this knowledge should be systematically transformed into the engineering domain. Comprehensive studies performed on the literature reveal the drawbacks of the existing bioinspired design (BID) approaches and processes. It is well observed that the gap between biological domain and engineering domain has not been completely filled in the existing BIDs. This drawback prevents an effective knowledge transfer from biological domain to engineering domain. Moreover, a well accepted systematic process for selecting and analyzing biological systems is not available in the existing BIDs. This research aims at developing a systematic BID methodology in order to overcome the drawbacks of the existing BIDs and promote research on BID methodology.

It is 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 shows that the main difference between BID methods and systematic engineering design methods are only observed in the conceptual level of engineering design. Thus, the main concentration of this thesis study is on the bioinspired conceptual design (BICD) methodology.

It is proposed that bioinspired products are classified into three groups. The first of these groups is bioinspired artificial design products which are inspired from function, morphology and/or behavior of biological systems. The second group is designed by inspiration from structures which are built/made by biological systems. The third group is bioinspired natural products which are either biological systems with some embedded electronic/mechatronic parts or artificial systems working together with part of live biological systems. The thesis work focuses on the design of bioinspired robots (biorobots) which belong to the first group, i.e. bioinspired artificial products.

Main focus of this research is to develop a BICD methodology, rather than designing “perfect” biorobots. Conceptual design procedure for biorobots is investigated in case studies so as to generalize the BICD procedure. This investigation is limited to experimental facilities and analysis of biological systems. This from experimental view, only jointed-leg locomotion is considered as a motoric action. Sensors and control architectures are left to further research.

Two types of BID as the problem-based (PB) BID and the solution-based (SB) BID are considered in the literature. The difference between these approaches is based on starting point of the design process. In PB-BID, the design process starts with an engineering problem, whereas SB-BID starts with a biological system which can be used as a solution for an undefined engineering problem. The design process is initiated in the engineering domain, continues in the biological domain and finally the process is completed in the engineering domain in the PB-BID. The design process starts in the biological domain for the SB-BID, and it is completed in the engineering domain. However, during the case studies, it has been realized that the BICD process should begin in the engineering domain. Hence, the suggested BICD methodology starts with customer’s needs and it is completed with a conceptual design of a biorobot. The methodology represents design activities performed in both biological and engineering domains, so as to form an interpreted process structure for both PB-BICD and SB-BICD.

A BICD methodology is proposed and developed with six steps in order to transform the customer's needs into the design concept of a biorobot. These steps are discussed as follows:

1. Task Clarification: This step provides a mapping between “customer needs” and “functions and constraints of the design product” In the design literature, some systematic methods are described to convert customer needs into product specifications that include functions and constraints. However, any implementation on BID does not exist. A requirements list is used to categorize the customer needs and then, sets of functions and design constraints are obtained using the list in the BICD methodology. Although this systematic method is proposed for this step, the mapping operation is largely dependent on designers' experience. Further research is required on this topic to reduce the effects of the experience.
2. Biological System Selection: In this step, breed(s) of biological systems are selected. For SB-BICD, the specie of the biological system is known and the designer only selects the breed(s) of the biological system while for PB-BICD both the specie(s) and the breed(s) are selected in Biological System Selection step.

The designer can select either one (breed of) biological system for all functions (i.e. a Terrier dog for walking and trotting) or different biological systems for the required functions (i.e. an American lobster for walking and a Terrier dog for trotting) in this stage. Selection of multiple biological systems results designing hybrid biorobots. Unlike the existing BIDs which are used as single biological system, the developed BICD methodology allows the designer to develop concepts of biorobots which can be inspired from single or multiple biological systems.

The selection of the biological system is also dependent on the designer's own experience and preferences. Features of the selected breed(s) may affect the design parameters of the final product. As an example, if a Terrier dog and Kangal dog are compared, it is observed that the Terrier dog trots with a low speed while the Kangal needs a higher speed due to Kangal's long legs. Hence, it can be said that the expected biorobot velocity during trotting depends on the selected breed of biological system for this example.

3. Biological System Analysis: This stage provides required knowledge about the selected (breed of) biological system. In this thesis, two approaches are used to determine the required knowledge. The first one is the studies on biorobot definition and the second one is the studies on existing case studies of biorobots. A semantic network is developed to represent the relations in biorobot definitions and concepts used in existing case studies and given in the related chapter. The representations show that knowledge about biological system should cover morphology, function and behavior.

Unlike the Gero's function-behavior-structure (FBS) model [Gero and Kannengiesser, 2002], in this thesis work, morphology-function-behavior are proposed to obtain required knowledge about the biological system and then, the knowledge should be transformed into engineering system. Morphology is used in the methodology because the morphology covers information about form as well as structure of biological systems. Hence, the morphological information includes dimensions, weight, forms of limbs/links and body structure details (the number of links, joint details, etc).

Function gives information about what the biological system does. In this research, function is limited to jointed-leg locomotion types such as walking and running. During the studies, morphology of the biological systems that is related with the interested function is considered. For example, when jumping motion of a grasshopper is studied, only hind legs of the grasshopper are analyzed because jumping is performed by the hind legs whereas the fore and middle legs are only used to elevate the body before takeoff.

Behavior gives information about how the biological system performs the interested function. In the research, only visual (physical) behavior is considered because physiological and neurological behavior of biological systems is not investigated in the scope of the thesis.

Two methods are implemented to obtain the knowledge about the biological system which should include information of morphology, function and behavior. The first method is the content analysis in which literature survey can be carried out and the second one is the observation method in which an experimental set-up is developed and used to analyze the biological systems.

During the research, fourteen biological systems and twenty four locomotion types are investigated. Three of these investigated biological systems are analyzed by using content analysis method while the others are analyzed by using both content analysis and observation methods. In the research, four biological systems among the all investigated biological systems are selected as case studies in which all steps of the developed BICD methodology are implemented. These case studies are a dog biorobot (BioDog) for walking and trotting, a cockroach biorobot (BioCoc), a jumping (grasshopper) biorobot for jumping and a hybrid (dog and lobster) for walking. They are given in Chapter 5 in detail.

During the case studies, observation method is utilized to collect functional and behavioral data while content analysis method is preferred to obtain morphological data. An experimental set-up is constructed with a one head high speed camera, a computer, an appropriate lighting system and proper supplementary equipment such as treadmill to observe biological systems' locomotion behavior. During the studies, interested morphology of the biological systems is collected and organized in a set of information consisting the number of legs, pairs of legs (based on anatomic structure), limbs of legs, forms of limbs, joints of legs, types (structures) of joints, muscle structures (if required), etc. For functional knowledge, a set of information about the interested locomotion type of the biological system and kinematics data of the joints is derived. The behavioral knowledge is also considered in a set of information in which pairs of legs moving together (based on the type of locomotion) and leg combinations (swing and stance phases of legs) are given.

The experiments on the case studies show that the experimental set-up can be improved in order to gather more precise data about the biological system. For instance, during the experiments, 2D video records are captured and 2D data are transformed to 3D by using animals/insects symmetry or 3D video images are obtained using a mirror. However, the number of camera head would be increased to directly record 3D video images which provide to collect more precise data by following whole body motion simultaneously.

4. Bioinspired Transformation: In this step, the knowledge transformation from the biological domain to the engineering domain is performed. A suitable method for this transformation is proposed and developed in this research. During the case

studies, morphology about the biological system is transformed into engineering system by matching forms and structures of biological systems with engineering ones. In this stage, locomotion cycles, which should be repeated by expected biorobots during the locomotion, are obtained. The joint angles and the leg combinations of the biorobot are evaluated and modeled with respect to the cycle information, so function and behavior of biological systems are transformed into a biorobot.

If sufficient numbers of biological systems are analyzed and the knowledge about biological systems can be transformed into the engineering domain, a database about biological systems in the engineering domain can be created. Thus, without analyzing the biological systems, biorobots can be designed by use of the database.

5. Engineering Structures Generalization: This step as a well-known engineering design step provides alternatives of engineering structures/components by using the knowledge about the biorobot. In this study, a morphological matrix is used to collect generated structures/components for materials, joints, actuators and controllers of the biorobot. Details are given in Chapter 3.
6. Engineering Structures Selection: In this stage, concept alternatives are generated and a conceptual design of the biorobot is selected among the alternatives by using an evaluation method. Weighted Rating method is used as an evaluation method in the case studies. All generalization and selection of (biological systems' and engineering structures') alternatives are dependent on the designer's experience in the BICD process and in future studies, they should be automated to reduce the experience effects and to increase creativity.

Main contribution of this thesis research is to develop a BICD methodology for the design of biorobots. Within the aim of the thesis, a BICD process is defined with a formal representation to contribute systematic process modeling of linguistic BID approaches in the literature. In the studies, the model alternatives and the process's features have been compared for the formal representation of the process. The DEVS (Discrete Event System Specification) formalism was selected among others to model the BICD process because states of the BICD process can be defined and transitions between states and effects of the inputs/events on the final design can be observed in the DEVS model.

The performed thesis study should be considered as an initial step of the systematic BICD methodology development. Additional studies which are suggested as future work should be performed to improve the developed methodology.

## **6.2 FUTURE WORK**

Suggestions for further work are categorized in two groups. The first one is related with the scope of the thesis. Although the developed BICD methodology has several advantages, it could not be enhanced without some assumptions which bring a set of simplifications for the developed methodology. In future studies, these simplifications should be reduced to expand the application area of the methodology. These simplifications and proposed suggestions are listed as follows.

- The main concentration of this thesis study is the bioinspired conceptual design (BICD). The other phases of the BID can be performed with the other engineering design phases and steps. In the future, a case study may be applied with a BID process.
- This study is focused on design of biorobots. Bioinspired products are classified into three different groups and biorobots are a subset of one of these groups. Implementation of the developed BICD methodology on the remaining bioinspired products should be performed.
- The biological systems for the case studies have been selected according to their locomotion types. Jointed-leg locomotion has been preferred to simplify the biological system analysis. As a future work, different motion types, such as flying, can be implemented in the developed BICD methodology and minor modifications on the methodology should be performed.
- Sensors and control architectures should also be considered within the BICD methodology in future research.
- In order to develop a BICD methodology, DEVS model is used for formal representation of the BICD process. Although the DEVS used in the thesis is suitable for initial step of the developed BICD methodology, the DEVS should be improved or a new modeling method should be integrated to the methodology for a better mathematical model representation of the BICD process to observe effects of inputs on the final design.

- The proposed BICD methodology has to be performed manually and the designer is not able to see the effect of any input parameter change during the design phase, unless the design is completed. The developed BICD methodology can be automated to allow the designer to observe the effects of input parameters on the final conceptual design during the design process.

The second group of suggestions is related with the implementation of the case studies. During the case studies, the following studies have been performed manually;

- generalization and selection of biological systems,
- generalization and selection of engineering structures,
- decision of expiration times of the steps/states,
- selection and rating of evaluation criteria and
- selection of a design concept for a biorobot

In order to reduce the effect of designer's experience on the BICD process, these steps should be automated in the future. Another suggestion for future research is the development of a bioinspired design database by analyzing sufficient number of biological systems and transforming knowledge about them into engineering domain.

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## **APPENDICES**

## APPENDIX A

### GLOSSARY

**Anatomy** is the branch of morphology and studies the structure of body parts and their relationships.

**Behavior**, which can implement different functions, is a sequential change of states over time with respect to change in the internal state of the body or in the environment.

**Biomechanics** is a science that study of forces interacting with living systems.

A **component** is a part of a system.

**Design methodology** includes a design process model and a set(s) of methods.

**Design procedure** is an individual way of a designer to perform a design task.

**Design process** is a systematic application of a design procedure.

**Ecology** refers a relationship between biological systems and their environment.

An **event** is a point in time that designates a change in state.

**Form** refers to visual appearance.

A **function**, performing tasks, includes a relationship between input and output of energy, material, and information.

A **mechanism**, performing some functions, is a part of a machine including components.

**Morphology** is a science dealing with the form and structure of biological systems without consideration of function.

**Physiology** is a science concerning the function of biological systems.

**Stance** represents a phase in which the leg is contact with the ground.

A **state** is a system description for an interval of time.

A **structure** is an internal configuration of a system in which the components of a whole are assembled.

**Swing** represents a phase in which the leg is not contact with the ground.



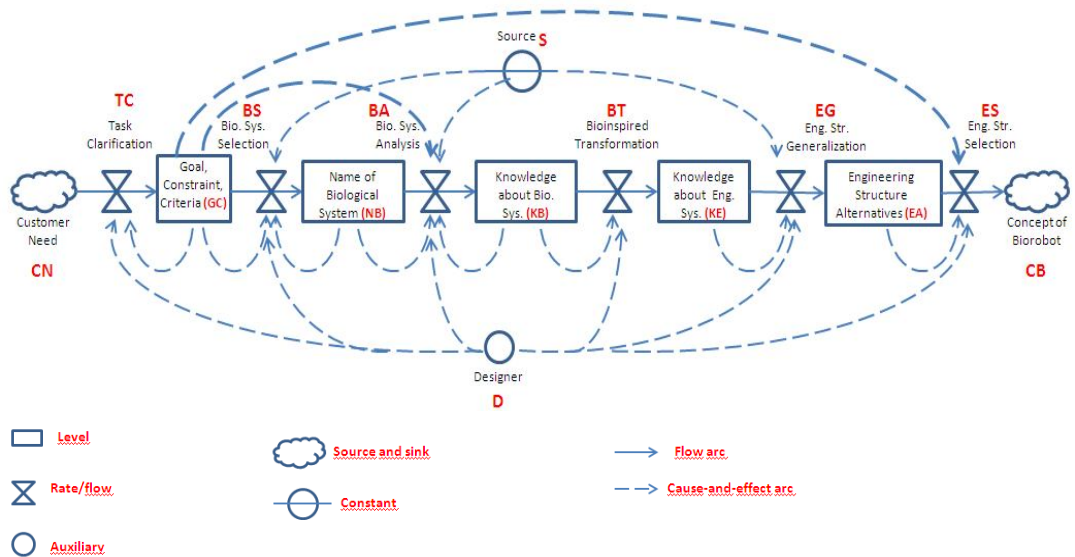


Figure B.2 Flow graph (Forrester Diagrams or Stock-flow Diagram) of the process

In Figure B.2, some representations are used. These are explained as

**Level:** is a quantity that accumulates over time.

**Rate/flow:** changes the values of levels.

**Auxiliary:** arises when the formulation of a level's influence on a rate involves on or more intermediate calculations.

**Source and sink:** Source represents systems of levels and rates outside the boundary of the model. Sink is where flows terminate outside the system.

By using the Forrester diagram, mathematical equations are derived, given in Equations from B.1 to B.12.

$$\frac{dGC}{ds} = TC - BS \quad (B.1)$$

$$\frac{dNB}{ds} = BS - BA \quad (B.2)$$

$$\frac{dKB}{ds} = BA - BT \quad (B.3)$$

$$\frac{dKE}{ds} = BT - EG \quad (B.4)$$

$$\frac{dEA}{ds} = EG - ES \quad (B.5)$$

$$\frac{dCB}{DS} = ES \quad (B.6)$$

$$TC = f_1(CN, GC, D) = CN + -k_1 * GC + k_2 * D \quad (B.7)$$

$$BS = f_2(GC, NB, D, S) = k_3 * GC - k_4 * NB + k_5 * D + k_6 * S \quad (B.8)$$

$$BA = f_3(GC, NB, KB, D, S) = k_7 * GC + k_8 * NB - k_9 * kb + k_{10} * D + k_{11} * S \quad (B.9)$$

$$BT = f_4(KB, D) = k_{12} * KB + k_{13} * D \quad (B.10)$$

$$EG = f_5(KE, D, S) = k_{14} * KE + k_{15} * D + k_{16} * S \quad (B.11)$$

$$ES = f_6(EA, GC, D) = k_{17} * EA + k_{18} * GC + k_{19} * D \quad (B.12)$$

If Equations B.7 to B.12 are substituted inside of Equations B.1 to B.6, the general equations can be generated as Equations B.13 to B.18.

$$\frac{dGC}{ds} = -(k_1 + k_3)GC + k_4NB + (k_2 - k_5)D + CN - k_6S \quad (B.13)$$

$$\frac{dNB}{ds} = (k_3 - k_7)GC - (k_8 + k_4)NB + (k_5 - k_{10})D + (k_6 - k_{11})S + k_9KB \quad (B.14)$$

$$\frac{dKB}{ds} = k_7GC + k_8NB - (k_9 + k_{12})KB + (k_{10} - k_{13})D + k_{11}S \quad (B.15)$$

$$\frac{dKE}{ds} = k_{12}KB + (k_{13} - k_{15})D - k_{14}KE - k_{16}S \quad (B.16)$$

$$\frac{dEA}{ds} = k_{14}KE + (k_{15} - k_{18})D + k_{16}S - k_{17}EA - k_{19}GC \quad (B.17)$$

$$\frac{dCB}{ds} = k_{17}EA + k_{18}D + k_{19}GC \quad (B.18)$$

By using the Forrester diagram representation, equations were generated for the steps, inputs and outputs of the BICD process. Unfortunately, it is seen that these equations are not meaningful and the relationships between steps are not demonstrated. In future, this approach can be significant.