Petri Net Modeling and Simulation of Walking Behaviour for Design of a Bioinspired Robot Dog

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Abstract: Research in behavior-based design faces many challenges regarding the aids in conceptual design of biorobots, representation of a biological system's behavior in a well formed modeling tool and therefore providing systematic transformation of this behavior into robot design. This paper reports a research that focuses on the development of a Petri Net model to represent a biological system's behavior. The model is based on real time data collected from an experiment in which a dog is walking on a treadmill with a speed of 1km/h. The model has the ability of simulating the real time rhythm of dog's walking behavior utilizing colors and numbers as well as the step-by-step simulation. The aim is to observe the behavior of a walking dog in time domain as an early stage of conceptual design of a bioinspired robot dog. Main challenge is to develop a methodology to guide designer towards more creative designs based on bioinspired design ideas. The presented work is an early attempt to initiate a systematic approach towards the stated goal.

1 INTRODUCTION

Bioinspired design methodology utilizes analogous biological phenomena to develop solutions for engineering problems. Inspiring design ideas from functions, behaviors, structures, materials, and form of biological systems is a challenging process for engineers and designers, and it encourages development of creative designs. However, it is not a straightforward engineering activity; it requires high level balanced expertise on both domains. Moreover, biologists and engineers use different concepts and terminologies so that there is always difficulty when biological phenomena are transformed into engineering domains. Many studies focus on constructing bioinspired design (BID) methodologies to eliminate these disadvantages and help designers to develop creative and innovative products. Bioinspired conceptual design (BICD) methodology (Konez-Eroglu et al., 2011a) was developed for the design of hybrid bioinspired robots which can be inspired from multiple biological systems. An important problem in bioinspired design is that once designers identify a target biological system to be inspired, they must obtain necessary knowledge for the solutions applicable to their design problem. One of the important types of knowledge is the behavior of the target system. Rapidly growing experimental possibilities allow researchers to represent behavior of biological systems into powerful modeling and simulation tools. In particular, bioinspired robot design requires imitating behavior of the biological target system on a physical robot. Therefore, a deep understanding of the biological system behavior is of great importance for designers to extract underlying behavioral principles and to convert them systematically into a biorobot design.

This paper presents a case study towards development of a systematic approach for converting experimental data of a biological system behavior to a model framework that can be used in engineering domain. In this study, a Petri Net model for walking behavior of a dog is developed based on an experimental data recorded using a high speed camera. The model is capable of representing and simulating the dog's walking behavior as an 8-state walking cycle with the associated time periods for state transitions. The model structure is composed of a brain-unit and a leg-unit for modularity. A Petri Net model was developed and simulated using Artifex™ graphical modeling and simulation environment, which is a C++ based software tool. The model is used to validate the deadlock free

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walking behavior of a robot dog at conceptual design stage.

The paper is organized as follows. Next section presents a brief overview of the bioinspired design (BID) methodology with special emphasis on the importance of behavioral modeling for conceptual BID. Then, the Petri Net model architecture for the walking behavior of a dog is explained and simulation results are given. Finally discussion and conclusions regarding the current study are provided together with the intended future research directions.

2 BEHAVIOURAL MODELING IN BIOINSPIRED DESIGN

Capturing a natural system's task accomplishment behavior, and re-creating a qualitatively similar behavior in an artificial system is one of the most interesting research issues in the field of robotic design methodology (Fleischer and Troxell, 1999). Thus a new robot design methodology has been emerged so as to develop behavior based robot architectures. Behavior based robotic architectures can be developed systematically using bioinspired design (BID) methodologies. Bioinspired design (BID) needs a systematic method for transformation and it uses analogical reasoning approach in which the source domain is the biological domain while the target domain is engineering (Mak and Shu, 2004;Wilson, 2008;Tsujimoto et al., 2008; Nelson et al., 2009; Helms et al., 2009). There are two approaches in BID studies with respect to starting point of the design; problem-based BID (PB-BID) and solution-based BID (SB-BID). PB-BID starts with an engineering problem in engineering domain whereas SB-BID begins with a biological system in biology domain.

Modeling the behavior of a biological system is a challenging topic within the framework of developing a systematic Bioinspired Conceptual Design (BICD) process model (Konez-Eroglu et al, 2011a) given in Figure 1. The suggested BICD process is developed to provide design concepts of bioinspired robots, *biorobots*. Based on the existing literature (Webb and Consi, 2001; Bar-Cohen, 2006; Meyer and Guillot, 2008), bioinspired robots can be defined briefly as follows;

Biorobots, biologically inspired (bioinspired) robots or biomimetic robots, emulate the functions and performance of biological systems, look like inspiration model and behave similar to the original model. Biorobots can be decomposed under sensoric, motoric and cognitive sub-systems.

This definition is structured in a semantic network representation (Konez-Eroglu et al., 2011b) shown in Figure 2, so as to clarify the relationships between various concepts. Among these concepts, "behavior" is the main concern of the current study. 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.

In the BICD methodology, one of the important problems is to collect information about the behavior of a biological system and develop a model to represent the behavior. Then, the model can be used to transform the biological system's behavior systematically into engineering system's (biorobot's) behavior. Behavioral modeling is described as one of the modeling approaches in engineering design methodology and defined as a channel category of the design knowledge stream (Horvath, 2004). It is an important method in engineering design to establish a framework for developing virtual prototypes (Shen et al., 2005). Behavioral models and their software implementations allow designers to represent design artifacts as technical systems and to analyze compare and evaluate their possible behavior at an early design stage in a short time. In a previous research, Discrete Event System Specification (DEVS) and Petri Net formalism were used for modeling the operational behavior of educational robots during conceptual design (Erden, 2010; Erden 2011).

Behavior of the robot was defined as composed of states and state transitions independent of any physical embodiment. Quadruped walking behaviour has been investigated in various research studies (Griffin et al., 2004; Pongas et al., 2007). In the BICD process, behavioral modeling of a biological system is based on observing states of the system behavior and understanding how transitions occur between the states. In this study, an experiment has been conducted to observe walking behavior of a dog to determine states and state transitions. Behavioral model is developed using Petri Net formalism (Peterson, 1977; Murata, 1989) with the Artifex™ graphical modeling and simulation environment as the software tool. We selected to use Petri Nets in this study due to the simplicity of describing states and state transitions graphically as well as due to the possibility of translation into mathematical-logical expressions. These advantages also lead several researchers to model robot behaviours using Petri Nets (Kobayashi et al., 2002;

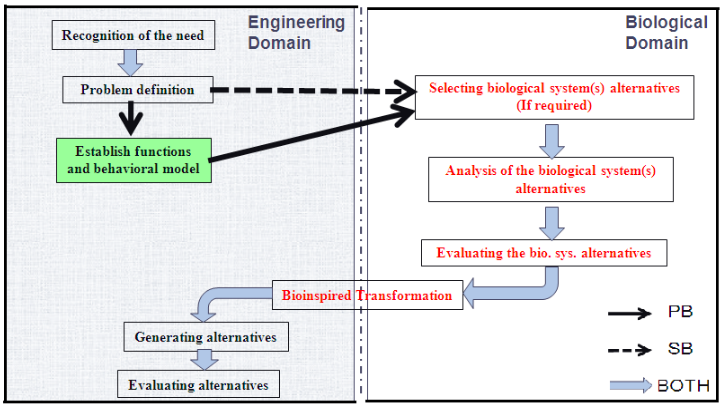

Figure 1: PB-BICD and SB-BICD phases in BICD (Konez-Eroglu et.al, 2011a).

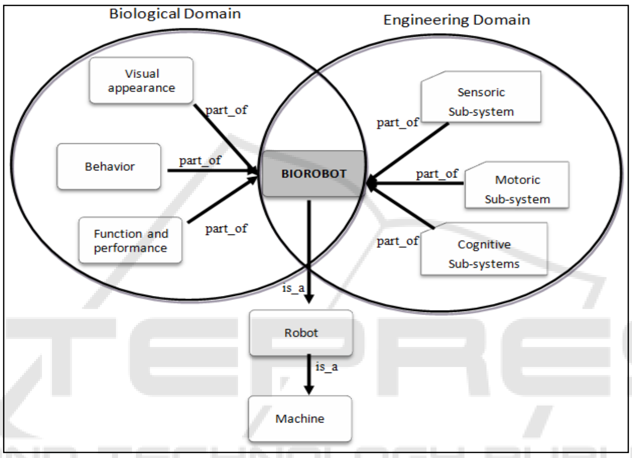

Figure 2: A semantic network representation of a biorobot (Konez-Eroglu et.al, 2011b).

Guangtao et al., 2003; Serhan et al., 2008; Vladareanu et al., 2011).

3 PETRI NET MODEL ARCHITECTURE FOR A DOG'S WALKING BEHAVIOUR

This section includes detailed information on the Petri Net model developed for the representation and simulation of the walking behavior of a dog in the Artifex™ software environment. The aim is to observe and systematically represent walking behavior of a dog in time domain.

A high speed camera was used in the observation phase of the study. A Photron Fastcam MC-2 Color 10K high speed camera (512 x 512 pixel) with Navitar TV zoom 8.5 - 51 mm lens and two Megaman 60 W cold lighters were used. A terrier type dog with a mass of 3.7 kg was used in the experiment. The dog walked freely on a treadmill. The experimental set-up is shown in Figure 3. Since the camera consists of one head, two dimensional video images were obtained. The dog's walking behavior was recorded with 1000 fps with 376 x 484 pixel resolution videos. TEMA™ Motion 2D software program was used to analyze the dog's walking behavior and obtain the time data.

Time data for the Petri Net model was collected with an experiment in which the dog's walking speed is 1km/h. Walking period is divided into *tours* as shown in Figure 4. A *tour* is the time duration in which all legs take one complete step with 8-states represented by UP and DOWN positions of the legs. Duration of each tour is 704 ms and Figure 4 represents time data for 3-tours.

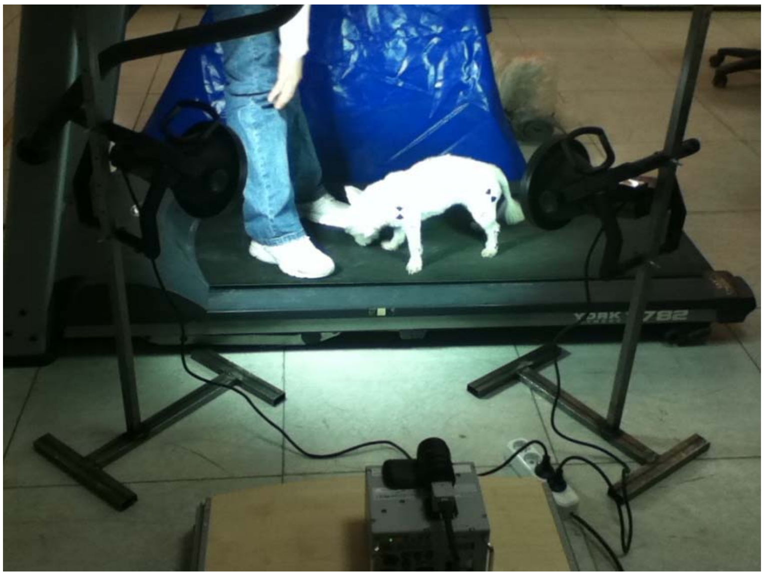

Figure 3: Experimental set-up for recording a dog's walking behavior.

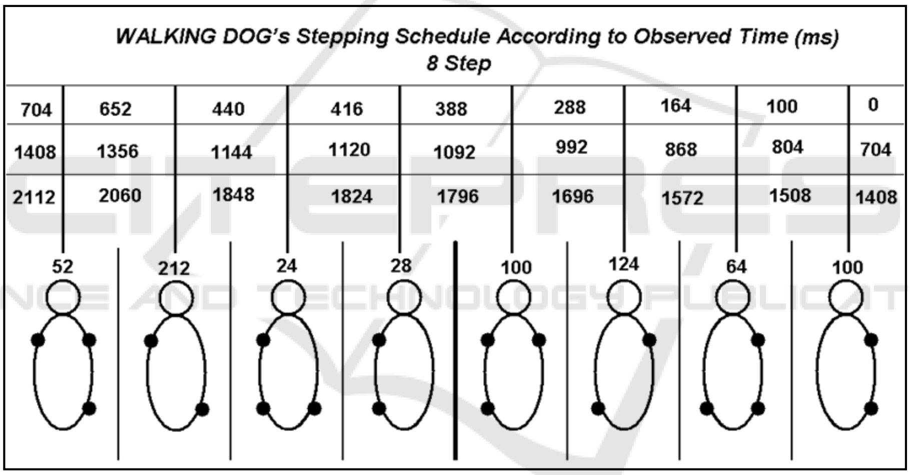

Figure 4: Walking dog stepping schedule obtained from the experiment.

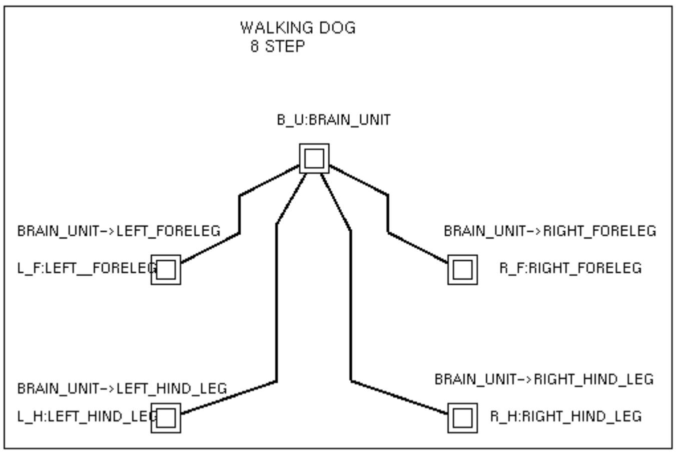

Figure 5: Top level Petri Net model of the dog's walking behavior.

In the Petri Net model architecture (Figure 5), five objects are used to represent behavior of the dog's body organs that contribute its walking; these are *a brain unit* and four leg units (*a left foreleg, a left hind leg, a right foreleg and a right hind leg*). The model has the ability of simulating the real time rhythm of dog's walking by means of different colors (as blue and red) and states (numbers); as well as the step-by-step simulation in virtual time. During the simulation, *the brain unit* counts the number of tours and expresses that by a state (number) and color of the related *leg unit*. Behavior of each *leg unit* is simulated in real time such that DOWN position is represented by the number “0” and color “blue” and UP position is represented by the number “1” and color “red”. Each object in Figure 5 is modeled with an associated Petri Net. Linksets are used to connect the leg units in the model architecture with the brain unit. Petri Net models of the brain unit and left foreleg are shown in Figure 6 and Figure 7, respectively.

Brain Unit (Figure 6) contains a place (*START_BRAIN)* and a transition (*CONVEY)* alongside eight columns of components (places and transitions). The place START_BRAIN contains an initial token which operates as a starting signal in the brain and is propagated throughout the eight columns of components which represent the brain cells.Brain columns include two transitions, one normal place, one input place (represented by two concentric circles) and two output places (represented as a triangle inside a circle). Input and output places have the task of communicating with other units (legs) in the model. Each two brain columns operate as the control mechanism of one leg, one for the *UP* position of the leg and one for the *DOWN* position. Each position has an active period and an inactive period. It means for instance for the DOWN position, the leg is on the ground during the active period and it is lifted during the inactive period. DOWN and UP positions are exactly converse of each other on the time domain. Each position (DOWN or UP) has an initial delay alongside the active and inactive durations. In the Brain Unit, initial delays are set in the upper transitions and the active period durations are inserted in the lower transition while the durations for inactive periods are set in a transition in the Leg Unit. The black diamonds at the bottom part of Figure 6 are *Portset*s which are used to connect the brain to other units (legs) through *Linkset*s. Linksets are like multi-wire cables and the portsets are like the terminals that those cables are connected. All the input and output places connecting the brain to each leg are linked to the related portset. This procedure is repeated in each unit as well.

Similar to the Brain Unit, Petri Net model for the Leg Units are composed of two main parts to represent DOWN and UP positions. As an example, Petri Net model of the left foreleg is given in Figure 7. The right side models *DOWN* and the left side models *UP* position of the leg. Each part consists of three transitions, one normal place, two input places and one output place. Inactive period duration of the leg position is set in the upper transition and the two lower transitions have the duty of conveying the

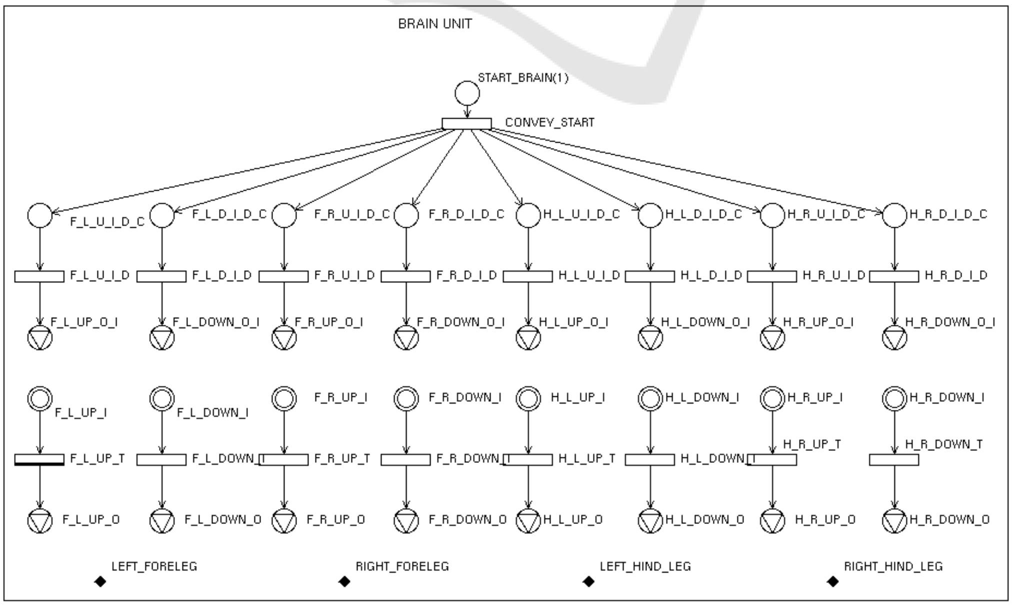

Figure 6: Petri Net for the Brain Unit.

brain command to the leg during the initial delay and active period duration. The upper transition also contains some C++ codes to set the illustrating colors and states (numbers) of the model.

4 MODEL SIMULATION

Figure 5 shows the top level page of the Petri Net model for the dog's walking behavior in Artifex™ Model Editor environment. All units in the model architecture are illustrated at this level. Figure 8 illustrates a screenshot from the simulation environment of the software. The figure depicts the model at instant 1848 ms in the 3rd tour. As for the legs, *One* and *Red* express the *UP* position, while *Zero* and *Blue* express the *DOWN* position. Numbers and colors at the brain simply count the tour number. Simulation can be carried out both step-by-step in virtual time and also in real time. Four measures, one for each leg, are defined in the model. These measures allow the designer to monitor the summation of time durations for which each leg is on the ground (DOWN position) during the total time of walking which is a specified number of tours the dog takes. It also let the user to observe the initial delay and final time gap of the DOWN position of the leg. It should be noted that the initial delays are given for the model only, because the model has to set the legs at the beginning and there is no such a delay in dog's nature. Table I shows total time durations for which each leg is on the ground for 10 tours.

The results and data collected from these measurements provide a more realistic and detailed viewpoint for the designer before stepping into the stage of designing and manufacturing a prototype of a robot. In a parallel research study, experimental data for the walking behavior has been used manually to design and construct a demonstrative

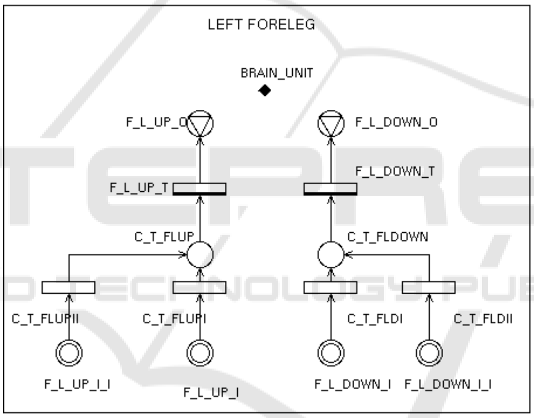

Figure 7: Petri Net for the left foreleg.

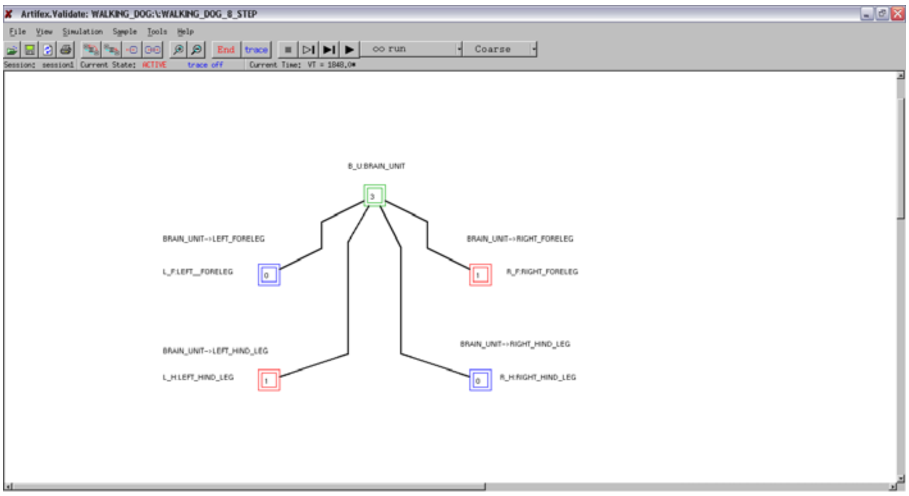

Figure 8: Screenshot of the graphical simulation of the dog's walking behavior.

Table 1: Time data for a measurement session.

	Beginning (ms)	End (ms)	Duration (ms)
Right Foreleg	652	6988	4400
Left Foreleg	288	6624	4160
Right Hind Leg	416	6752	4520
Left Hind Leg	100	6436	3400
Tour Numbers: 10	Total Duration: 7040 (704 each tour)		

prototype of a bioinspired robot dog. In the starting setting periods for legs, one can observe the total duration that each leg is on the ground and the instant that a leg steps up just before the end of each run. Therefore, these measures are used in the design and manufacturing process for checking and modifications as well as in the processor programming at the manufacturing stage.

5 CONCLUSIONS

Development of a model to represent and simulate the behavior of a biological system is a challenging research topic for the analysis of biological systems during the implementation of the Bioinspired Conceptual Design (BICD) methodology for design and manufacturing of biorobots. As a case study, this paper presents the development of a Petri Net model for a walking behavior of a terrier dog. The model is based on an experimental data for the states and state transitions during walking. States are represented as various combinations of up or down positions of the dog's legs. Model development and simulation has been done successfully using Artifex™ modeling and simulation environment. Four user defined measures have been developed to test the possibility of performance analysis based on the Petri Net model. These measures are not used for any evaluation, since the present study mainly focuses on developing a structured and formal representation of an unstructured and informal natural behavior with a well-known modeling tool. This case study shows that behavior of a biological system can be represented as a Petri Net model for simulation. Future research will be directed towards Petri Net model development for various biological system behaviors in different case studies and establishment of a generalized behavioral modeling method for BICD using Petri Nets. Another future work includes performance analysis of the model based on user defined measures.

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