# The Application Of Biomimetics To The Design And Control Of Multipedal Walking Robotic Platforms

### An Unnatural History of Walking Robots

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## Abstract

Walking autonomous robotic platforms have been the focus of research and development in the areas of robotics, engineering, intelligent systems and entomology for some decades now. In the area of robotics and engineering walking robots have an advantage over wheeled platforms, as most natural environments are not accommodating for wheeled vehicles, so walking should be a more versatile solution to navigating over variable terrain. In intelligent systems the interest is in how basic behaviours associated with locomotion, navigation and interaction with the immediate environment arise. In entomology and biology, artificial models have been researched and studied in order to test hypothesis and gain a better understanding of insect neurobiology and biomechanics.

Evolution has had millions of years to optimise its own systems, and as these systems are invariably optimised for robustness, versatility and efficiency, it is logical that engineers and scientists look to them for insight and inspiration in developing artificial systems. In this article, the various developments gleaned from a biomimetic approach to the control of multi legged walkers is examined, and how best to apply these approaches for future developments is discussed.

## Introduction

Wheels do not arise anywhere in nature, and much of the natural environment is not conducive to transit by wheeled vehicle. As such there has been a lot of interest over the previous decades in developing walking robots as an adaptable approach to navigation through variable and possibly hostile terrain. Some possible application for such platforms are; extra-planetary exploration, sea floor exploration, volcano exploration, disaster area search and rescue and subterranean research and exploration. The recent and ongoing situation at the Fukushima Nuclear Power Plant presents one situation where mobile robots are needed to navigate through a variable and damaged environment, too toxic for humans, and conduct technical operations. Arthropods offer an enticing avenue of research in the development of walking robotic platforms for a number of reasons. Arthropods represent some of the most successful and adaptable creatures on earth, able to inhabit any environment amenable to life, and make up 75% of all animals on earth *(Australian Museum, 2014)*. They have had 530 million years of evolution to optimise their system design *(Australian Museum, 2014)*, and yet present a much simpler system, both in regards to their biomechanics and neurobiology, than vertebrates. And as such, it has been observed that they seem to adopt a number of simple reflexive and reactive systems in order to overcome the problems of navigating variable terrain. As vertebrates would have also had to have overcome the same issues of legged locomotion in the natural environment, it is assumed that the lessons learned from the examination of arthropods will be equally applicable when designing more complex systems.

However, despite their relative simplicity, arthropods represent systems far more complex than anything currently possible in modern robotics today. Each insect leg contains thousands of specialised sensors, and a cockroach's antennae can have hundreds of thousands of sensors. Each insect leg can have between 5 and 8 DoF (Directions of Freedom), and spiders up to 10 DoF per leg, with additional joints between the body sections of some insects, leading to very complex mechanical system for control *(Fichter and Fichter, 1988)*. Thoracic ganglia in insects contain thousands of neurons and the head ganglia is a complex and sophisticated system of sensory processing, memory banks and motor control, and insect muscles are more efficient than anything currently possible in modern engineering (*Ritzmann, Quinn and Fischer 2004)*.Engineers also need to be aware that some scaling issues may not be applicable to the biomimetic approach when designing robots – certain aspects of insect biomechanics may be advantageous at the centimetre scale, but less applicable at the metre scale – this is certainly indicated by the study of animal biomechanics, when one observes the difference between the tetrapod gait of lower vertebrates such a salamanders and lizards – which has similarities to insect leg arrangements – and mammalian leg geometry, and the mechanical advantage it affords them(*Ritzmann et al 2004)*. Scaling issues are also a factor when considering the materials and their respective properties in robot design. A direct facsimile of biological systems and mechanics may be desirable in a biological scientific enquiry, where one is trying to gain greater understanding of the workings of actual insects, but from an engineering perspective, where one seeks practical outcomes, a choice must be made as to which aspects from biomimetic research are useful, and which to discard.

Even the control of a hexapod, with each leg reduced to three DoF *(Cruse 1976),* results in a robot with at least 18 DoF operating in a non-Cartesian space resulting in a computationally intensive operation for a traditional centralised controller.

The biomimetic approach to walking machines, with particular attention on arthropods has been approached from a number of directions; from the ground breaking new approach to cognitive systems using subsumption architecture developed by Rodney Brooks at MIT *(Brooks, 1986, 1989,1990, 1991)* , to the influential work on artificial neurons and insect walking neurobiology by biological cyberneticist Holk Cruse, to the more engineering based approach by Randall Beer, Roger Quinn and their teams over the years.

## Development of Robust Biomimetic Inspired Control Systems

### Genghis

Rodney Brookes first proposed his Subsumption Architecture as an alternative to the at the time traditional approach to AI, which was a top down, centralised approach relying on symbolic world models. Brooks instead took his inspiration from simple animals, viewing how they could successfully survive and navigate in complex and hostile environments, presumably without any higher cognitive functions or world model. From this he developed a bottom up approach to behaviours, driven by sensory input from the immediate environment, and consisting of Augmented Finite State Machines which affect each-others operation not through direct communication but through suppression or inhibition signals. This system was demonstrated with the Hexapod Genghis, and it proved that quite complex and adaptive behaviours could arise from fairly simple sets of rules.

## WalkNet

Holk Cruse, who has a background in biological cybernetics, and had done extensive research on the locomotion and reflexes of stick insects (Carausius morosus). Cruse had previously identified that while most insects had more DoF per leg, three DoF were enough to describe most of an insects locomotion (Cruse 1976).

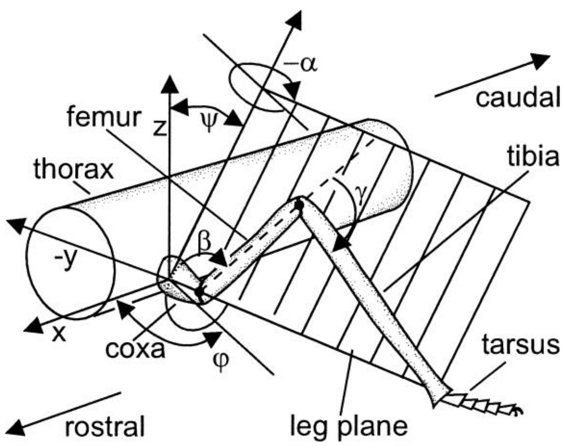


**Figure 1:** Schematic model of a stick insect leg showing the arrangement of the joints *(Cruse 1998)*

Wilson, Cruse and others have also identified a number of stereotypical gaits for walking insects; pentapedal gait at slow speeds (slow wave gait - only one leg in the air at any time) tetrapedal gait (ripple gait - four legs in contact with the ground at all times) and tripod gait at higher speeds. Two distinct phases in walking motion for each leg are also identified; stance, where the leg is supporting body weight, and swing, where the leg is moving forward through the air to its forward most step position.

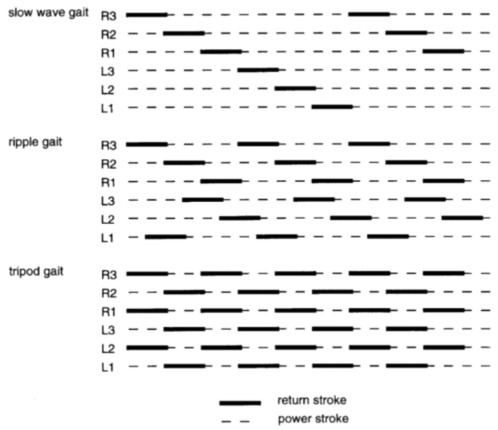


Figure 2: Common Insect Gaits (Wilson 1966)

Cruse took Brooks' subsumption architecture as the basis for developing a basic neural network representative of a reactive control system for walking insects. The network resembles an advanced state machine, with feed-forward controls and suppression/inhibition signals communicating between the different legs, but with no centralised control mechanism. Important control and sensor information for the system included the Anterior and Posterior Extreme Positions for the feet (AEP and PEP), leg joint angular position, relative body height, force feedback on the tarsus, and swing and stance angular velocity. Stability is maintained through a cardinal rule that a leg may only go into swing mode if none of its immediate neighbours are in swing mode. This has the notable affect that as the velocity of the insect increases, and the swing/stance period decreases, the insect gait converges from tetrapedal to tripod.

The other coordination influences identified by Cruse are illustrated in Figure 3. The coordination influences can also be scaled for walking systems greater than 6 legs. Posture – relating to the insect or robots body height, position and orientation, is controlled through a feedback loop from the angular position of the second joint in each leg. These observations and models were combined in a structural program of recurrent neural nets (RNN) called WalkNet. This system and model has been the basis for the majority of hexapod and octapod walking robot control systems subsequently. Even if the entire control architecture has not been used, at the very least the decentralised, feed forward coordination influence model has been used in the majority of multipedal walker control systems.

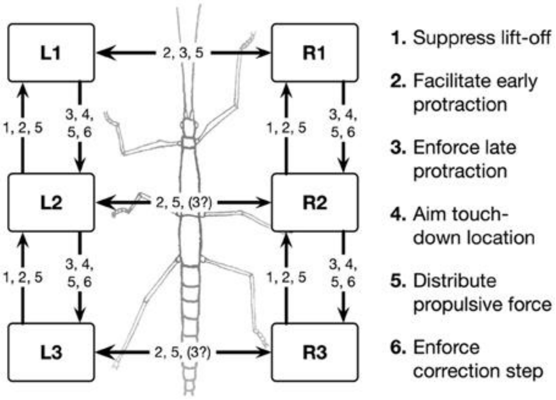


**Figure 3:** WalkNet coordination Influences *(Cruse 2013)*

## WalkNet – A Continued Evolution

The original WalkNet, built and tested in simulation only, had many shortfallings, much of which have subsequently been identified and remedied both by Cruse and by other researchers working with this architecture and applying it practically with a number of walking robotic platforms. Randall Beer, Roger Quinn and their team developed a number of additional functions in order to deal with obstacles or loss of footing in their robots, ROBOT I and ROBOT II – these included a searching reflex when gaps were encountered, an elevator reflex when taller obstacles were encountered, and a stepping reflex for correcting foot slippage (Beer et al, 1997). It should be noted that at the time Beer and their team were developing a similar Neural Network control algorithm to WalkNet, and that these reflexes were also later added to WalkNet and used in the TUM walking machine, MAX (Pfeiffer et al 1994)

Wait and Goldfarb provided further fine tuning in identifying problems that WalkNet had with real world dynamical situations involving gravity and stability (Wait and Goldfarb 2007) while Martin Gorner and Gerd Hirzinger (2010) and Schilling, Cruse and Arena (2006) have both independently added leg loss tolerance functionality to WalkNet – Gerd and Hirzinger building on Schilling et al earlier work.

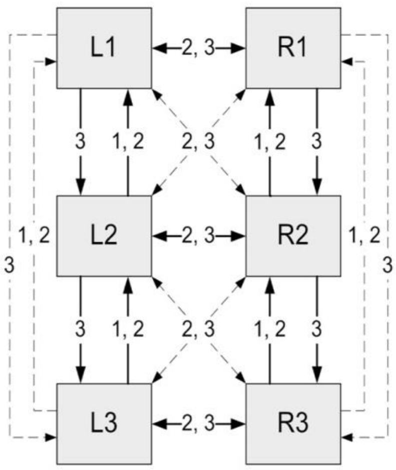


**Figure 4:** Cruse WalkNet Coordination influences with added bypasses to accommodate leg loss *(Gerd and Hirzinger, 2010)*

Gerd and Hirzinger also incorporate an omnidirectional navigation function in the application of WalkNet to their DLR Crawler, by defining the AEP and PEP as radii on a circle rather than points on a line parallel to the walker's body.

Higher functions have been also added to WalkNet with the addition of more RNN structures on a higher hierarchical level than the embedded control structure that WalkNet represents. NaviNet provides navigation functionality by influencing steering towards stored waypoints (Cruse and Wehner, 2011; Hoinville et al., 2012), and additional RNN's which model individual legs coupled to an RNN to represent the body in order to provide an internal body model, which aids error compensation during locomotion, and Motivational Network to further influence suppression and inhibition functions, as well as additional procedures for backwards locomotion and turning (Schilling et al 2013).

## SCASM and BILL Ant A

Another approach to a neural net based, decentralised sensor driven embedded control system for leg movement is Sensor Coupled Action Switching Leg Modules (SCASM) (Lewinger et al 2006). SCASM presents a further simplified reactive leg control mechanism, which has been used in conjunction with aspects of WalkNet still providing higher functionality such as gait control and navigation functions, and has been demonstrated to be effective on the BILL Ant A platform using low computational capable microcontrollers (Lewinger et al 2009). Further investigations into computationally economical methods for gait generation and hazard and obstacle avoidance are also being developed. This approach then demonstrates a further streamlining of computational demands for small independent systems which have a smaller energy and payload budget than larger platforms. It is unclear, however, whether this simplified system will scale for more complex or larger robotic walking platforms.

## Inverse Kinematics and Central Pattern Generation (CPG)

So far we have focussed primarily on WalkNet and similar systems, which seek computational economy by using embedded reactive systems in the form of RNN's, doing away, as much as possible, with any central processing and control. However an alternative and much employed approach to the control of walking robots is the use of Central Pattern Generators (CPG) and Inverse Kinematics with some sort of decentralised control network such as Cellular Nonlinear Networks (CNN). Central Pattern Generators are a centralised oscillator mechanism used to generate rhythmic patterned outputs with no sensory feedback. They are known to be present in biological neural networks, and are used in the context being discussed to provide the rhythmic signal to control the walkers walking gait. Inverse kinematics is a common concept in robotics for the control of non-orthogonal robotic arms and manipulators. It refers to the use of kinematic equations to determine the ideal angular position of the joints of a robot arm (or leg) when the desired location of the robots end effector (or foot) us known. Inverse kinematics can be problematic with the multiple DoF legs used in insect based walkers, due to redundancy, but a number of solutions have been identified (Nelson and Quinn 2001). CNN's or similar are modular networks that implement the CPG signal for locomotion and leg control. This architecture has a number of advantages as it has proven to perform well, and to be robust and reliable, and more versatile when it comes to implementing omnidirectional movement than the WalkNet based systems have tended to. They can also still employ some of Cruse's coordination interfaces at a direct world interface level, in order to maintain stability and gain environmental feedback (Cruse, 2003, 2006, Palmer III and Palunkar 2007, Arena et al 2004, Roennau et al 2010) .

The main drawback with this approach is it is more computationally demanding than more decentralised reactive systems such as WalkNet, requiring greater processing capacity and speed, and consequently using more power for control processes.

## Discussion and Conclusion

Robust and adaptable control systems for walking robotic platforms is an evolving and ongoing area of research and investigation, and the action of walking has proven to be far from trivial. This is in part due to the complexity of the systems being controlled, and in part due to the inherent unpredictability of the environments for which they are being designed. The field of robotics has benefited greatly from biomimetics and from an increased understanding of naturally occurring control systems, likewise biological cybernetics and neurobiology has been advanced through practical robotic experimentation. However, approaches and systems developed from trying to mimic nature should not be considered the ultimate goal of engineering design in this area, rather the practicality of the innovations developed through biomimetics should be evaluated to the task at hand and used in conjunction with more traditional engineering solutions, for the best possible outcome.

The streamlined, simplified, decentralised reactive control systems lend themselves particularly well to smaller systems with minimal spare payload and power budgets, while on larger walking platforms, the power consumption and weight of more powerful on board processors represents a much smaller proportion of the robots power and weight budget, so they can afford to have a more hierarchical hybrid system, employing WalkNet style control systems in combination with more computationally hungry control processes such as Inverse Kinematics and CPG, with a centralised processor for higher functions such as route planning, data analysis and environment mapping. This integrated approach will make possible the most robust and versatile solutions.

These hybrid systems should also be applicable to mobile autonomous platforms that have to operate in a variable environment other than ones modelled strictly on arthropod biomechanics – quadruped, biped, aerial and aquatic robotic platforms should all be able to benefit to this approach to integrated system control.

Outside of development of biomimetic robotics, these control structures could also be applicable to any complex control system that incorporates a combination of cyclic or rhythmic processes that also have to be adaptable to changed conditions from their immediate environment, in conjunction to longer term goal oriented planning.

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