A Biologically Inspired Investigation Into The Kinematics, Scalability And Control Of A Hexapedal Walking Robot

Dillon MacEwan, Deakin University, Student ID 211285035

Supervisor: Matthew Joordens

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. 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. However progress in this area has been slow due to the inherent complexity of designing control systems involving multiple directions of freedom.

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 team over the years.

Project Definition

The objective of this proposed project is to develop, design and build a hexapedal walking robotic platform in order to research the various design and control challenges in walking machines. The purpose of the project is to further examine any mechanical advantages to be gained from a biomimetic approach to the mechanical design of a hexapedal robot through the analysis of arthropod leg configurations, to examine the issues of scaling in regards to mechanical design power and actuation of hexapedal robots, and to build a functional testbed for the development of autonomous control and navigation functions.

The first stage will involve a biomimetic approach to the mechanical leg design, investigating the force distribution and posture found in various arthropod leg configurations, an investigation into whether there is any mechanical advantage to be gained from a non-homogeneous approach to the design of the separate leg pairs, as well as a comparative study of the kinematics of existing analogous mechanical systems found in hydraulic plant machinery such as backhoes and articulated cranes. From this an optimised leg design will be developed, and this design modelled for scalability, investigating the relative forces present under increasing loads and scale, and the structural and material requirements that would need to be met in the leg design as the scale and payload are increased.

The second stage of the design process will involve researching and modelling of various power systems and their suitability for different scale Hexapods. For actuation, the most likely options to be considered will be electromechanical servo driven actuation, electric over pneumatic and electric over hydraulic. For the power supply, stored energy battery power, with electric driven pumps for the pneumatic and hydraulic options, compressed air storage with battery electrics for the pneumatic option, and combustion engine driven hydraulic pump and electric generator will be considered for larger hydraulic systems. The pros and cons for each system will be considered, including cost, complexity and power to weight ratios.

In the third and most complex stage of the design will involve exploring and designing the AI and mechatronic aspects of the control system. In this stage all the locomotion functions as well as higher functions such as simultaneous localisation and mapping (SLAM) and route planning. A decentralised approach to gait generation and reflex actions in the individual legs will be considered, with a separate microcontroller running each leg, and actions determined by preset gait modes, feed forward information from the environment and the other leg controllers and feedback information from load sensors and joint positions. This control network will be based on the network architectures developed by Cruse and Quinn and employed in Holk Cruse's WalkNet system *(Cruse, H., Kindermann, T., Schumm, M., Dean, J., Schmitz, J (1998).* It is also proposed that the control system employs a centralised controller, for processing higher level functions such as route planning and processing more complex positional and visual data, and for sending the appropriate gait mode signals to the microprocessors – it may also function as a central pattern generator to this end. Appropriate sensors will also be considered at this point of the design – whether simple range detectors such as ultrasonics and infrared for obstacle detection, or these in conjunction with more sophisticated visual sensors – leg joint position measured either through angular potentiometers or actuator position, and load sensors in the legs. Further pose and position sensors such as accelerometers, gyroscope, magnetometer and GPS will also be considered at this point. Other considerations to be explored during the control design phase are gait and leg position correction on uneven terrain, detection and correction for low lying obstacles and potholes or small gaps through leg reflex actions *(W.A. Lewinger, B.L. Rutter, M. Blümel, A. Büschges and R.D. Quinn, 2006)*, and leg loss tolerance *(Martin Gorner and Gerd Hirzinger 2010)*. Pose control to optimise stability on non-level surfaces will also have to be considered.

Benefits

Walking robots have been the focus of much attention due to their versatility in navigating through unstructured environments that are inaccessible to wheeled vehicles, but progress in the development of functional walking autonomous robotic platforms has been slow due to the complexity of controlling multiple legs, each with multiple degrees of freedom, and the lower travel speeds and energy efficiencies possible compared to wheeled platforms. The complexity of the systems necessary have also meant that much of the larger platforms have had prohibitive costs associated with them, while the more common smaller platforms are limited in their application due to their size and associated payload capabilities. This project proposes to address these issues through analysing existing technologies and capabilities and developing a design strategy for larger hexapods. The potential applications for larger hexapod robots are for exploration of extraterrestial bodies and hostile environments, search and rescue operations in disaster zones, and operations in hazardous zones such as the Fukushima Nuclear Power Plant in Japan

Deliverables

The project is intending to deliver a design approach for a scalable autonomous walking hexapedal robot, and a functioning prototype testbed for developing control and navigation functions.

Literature Review/Research

As previously stated, there are a number of reasons motivating research into autonomous walking platforms, as well as numerous pitfalls and challenges that have made progress in this area slow. There is also considerable rationale in looking to nature for inspiration and insight into the design and control of walking robots, as evolution can be the best optimisation tool, as arthropods have had hundreds of millennia to develop the best evolutionary advantages through mechanical and energy efficiencies and through versatility *(Beer, R.D., Chiel, H.J., Quinn, R.D., Ritzmann R E , 1997)*.

Due to the complexity of the task, the designing of a hexapod platform involves a range of trade-offs between design requirements, functionalities, cost restrictions and component specifications *(Franco Tedeschi, Giuseppe Carbone 2014)*.

Mechanical Design

Mechanically it is worth doing a comparative study between arthropod leg configurations *(Wilson D 1966)*, leg geometries used in other hexapods and the forces acting in similar mechanical systems such as articulated crane arms or backhoes to further understand the strengths and weaknesses of these various configurations in order to come up with more optimal designs for specific requirements *(Kenzo Nonami, Ranjit Kumar Barei, Addie Irawan, Mohd Razali Daud, 2014)*. Factors to consider are the distribution of forces within the legs, the optimal configurations for speed, power efficiency, pose variability, stability and obstacle avoidance. For example a lower centre of mass will increase stability, but decrease the ease with which the robot can traverse obstacle strewn terrain, similarly, a wider span and spread on the hexapods legs may increase stability, maximum achievable velocity and the ability to traverse higher obstacles and wider ditches, but will decrease energy efficiency and increase the stresses in the leg components *(Franco Tedeschi, Giuseppe Carbone 2014,Nonami et al 2014)*. Another factor to be examined is what advantage, if any, is to be gained from a more biologically inspired non-homogeneous approach to the design of the separate leg pairs – i.e. – larger rear leg pairs with stronger actuators for thrust, and lighter more agile front leg pairs for reflexive obstacle detection and mitigation. Also whether there is an advantage to be had through a more radial arraignment of shoulder joints as opposed to a strictly rectilinear one, in regards to both stability and manoeuvrability *(Ritzmann, R.E., Quinn, R.D., Watson, J.T., Zill, S.N., 2000)*.

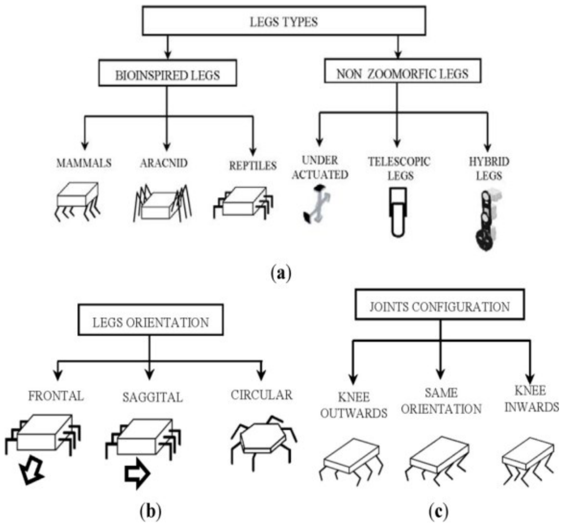

Figure 1: Different leg configurations for Hexapod Walkers (Franco Tedeschi, Giuseppe Carbone 2014)

Power

There are a number of power and actuation options that can be used in the design of walking robots. Servo motors are the most commonly used in smaller scale robotic platforms, as they are easily controlled, commonly available and relatively cost effective. With considerable improvements to battery technology in recent years, on-board energy storage or generation is becoming less of an issue. Linear motors offer the ability to provide fast reaction times and applied forces, but have not been used so widely in the area of walking robotics, possibly due less availability and greater cost when compared to servo motors *(Franco Tedeschi, Giuseppe Carbone 2014)*. Pneumatic cylinders can be cost effective, but lack stiffness and accuracy due to the compressibility of air, have a relatively low power to weight ratio, and have the additional drawback of having to carry an on board compressed air reservoir, and possibly compressor with additional power requirements. Air muscles or McKibben muscles offer superior power to weight ratio and reaction time, but still have the same controllability issues and power requirements *(Franco Tedeschi, Giuseppe Carbone 2014)*.. Hydraulics offer the best power to weight ratio, and good accuracy and controllability, and a favoured for larger machines, but the components can be heavy due to the high oil pressures required, the control of hydraulics is more complex than servo motors, and for independent mobility the systems require that the platform carry the additional weight of a hydraulic power pack – consisting of a pump and motor – typically internal combustion for larger systems. Considering this, there will be a lower size and weight threshold at which hydraulics will not be a practical option – it is a peripheral objective of this project to examine this threshold *(Franco Tedeschi, Giuseppe Carbone 2014,Nonami et al 2014)*..

Control

The control aspect of the project is by far the most complex, and as such has been the main area of focus for the literature review.

Hexapods have an advantage over quadrupeds and bipedal robots, as they are intrinsically statically stable, and therefor require less continuous processing that the platforms with less limbs require for dynamic stability, but have the disadvantage of having to control a greater number of actuators simultaneously *(Franco Tedeschi, Giuseppe Carbone 2014,Nonami et al 2014)*.. This can be computationally demanding for a centralised controller, so a number of strategies to cope with this issue have been employed by various researchers over the years. Most commonly a decentralised networked control strategy has been employed, with individual leg behaviour and motion determined by feed forward control from the environment and the states of adjacent legs, and feedback from some of the joint positions – these systems are designed to be reactive and to operate in real time *(Beer et al 1996, 1997, Cruse et al 1995, 1998, 2006)* . Some researchers have attempted to build hexapod navigation systems that are wholly reactive and decentralised *(R A Brooks, 1986, 1989, Lewinger and Quinn 2009)*, , while others have opted for maintaining a centralised processor for higher functions such as task planning and as a central pattern generator *(Paolo Arena,, Luigi Fortuna, Mattia Frasca, and Giovanni Sicurella 2004)*, as well as using more computationally demanding processes such as inverse kinematics *(Neslon and Quinn, 2001)*. The latter requires the design to have an increased payload capacity to accommodate the larger processing and associated power requirements.

Historical 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).

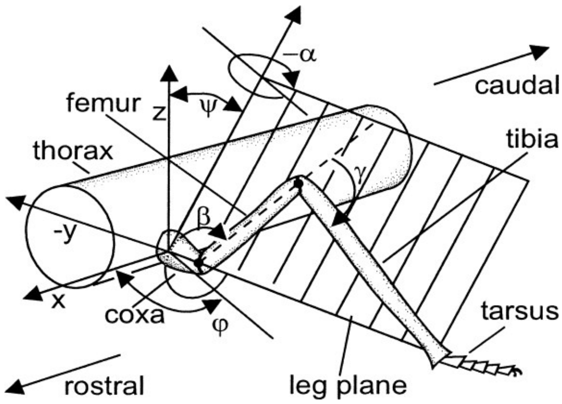

Figure 2: Schematic model of a stick insect leg showing the arrangement of the joints ***(Cruse 1998)***

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.

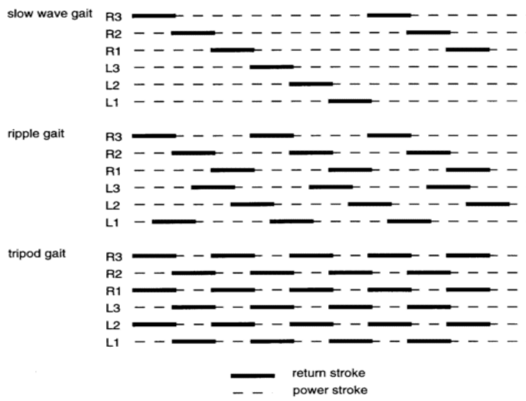

Figure 3: Common Insect Gaits (Wilson 1966)

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.

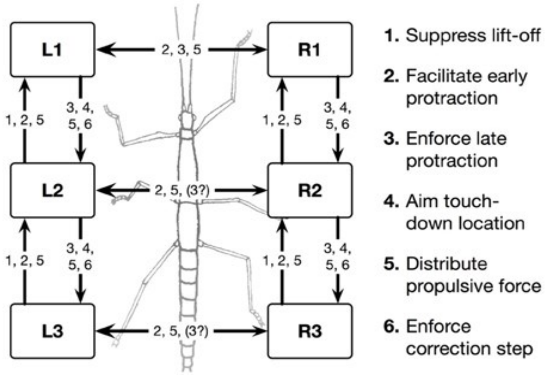

Figure 4: WalkNet coordination Influences (Cruse 2013)

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)

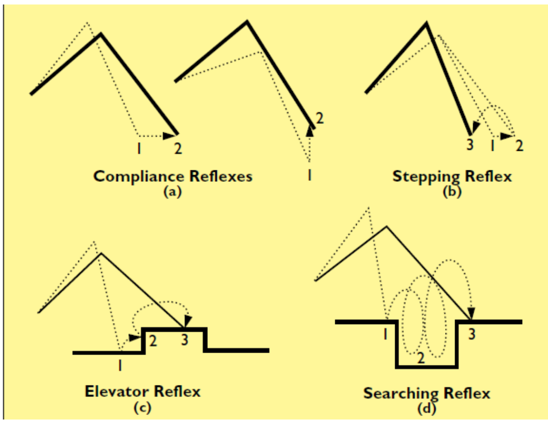

Figure 5: Leg Corrective Reflexes (Beer et al, 1997).

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.

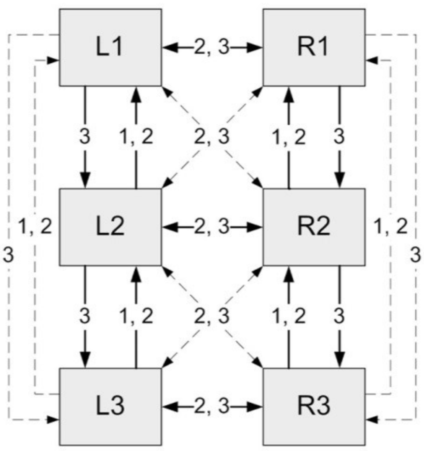

Figure 6: Cruse WalkNet Coordination influences with added bypasses to accommodate leg loss (Gerd and Hirzinger, 2010)

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).

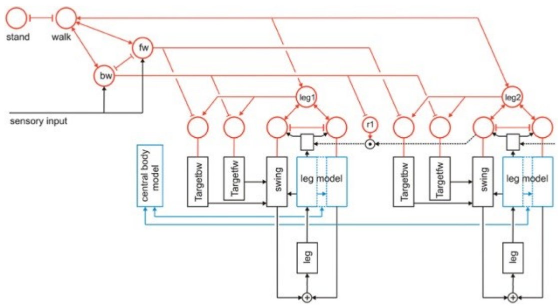

Figure 7: WalkNet with additional embedded mapping and navigation Nets (Hoinville et al., 2012)

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 this investigation has 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.

Given that the purpose of this project is to design a functional control system for a larger platform, the power consumption and processing speeds of the CPU are less of a concern as they would be for a lighter platform with a smaller payload and power budget. As such, a WalkNet inspired decentralised reflex driven gait and navigation control will be developed to optimise locomotion, but with a more hierarchical CPU based control structure for higher, more complex functions such as SLAM and route planning.

An algorithm for gait control will be developed which adopts a sliding scale for the delay between the swing phases of each group of legs – in this way the walking gait should converge from pentapedal to tripod in a smooth transition as it increases its locomotive velocity, and back again when obstacles are encountered or terrain variability increases. This scale can be pre-set from an initial scan of the immediate terrain to determine its smoothness, and therefor how easily traversed it will be.

For the research of this stage, a number of control structures, algorithms and programming languages will be evaluated from the appropriate literature and existing projects, then the electromechanical design will be designed and refined while the programming strategy is developed. The system will then be tested experimentally in stages once the prototype actuated platform, developed in stages one and two, is under construction. It is the goal of the project to have a completed hexapedal autonomous robotic platform with at least basic SLAM and navigation functionality, which can function as a test bed for further development of autonomous control and navigation functions.

Methodology

In brief, the methodology consists of physical/ mechanical design, modelling and simulation, building a small prototype test platform, including servos, sensor arrays, and control hardware, then; program, test, repeat.

The rough outline of the control algorithms will be first developed during the design and model phase and refined from there.

Mechanical Design

As previously described, for the mechanical design of the hexapod, the kinematics of existing arthropod leg configurations will be compares, as well as that of pre-existing analogous machinery such as hydraulic crane arms and back-hoe arms. The optimum design settled on will be modelled in Solidworks.

Modelling and Simulation

Once an appropriate leg design and configuration has been formulated, a model of the proposed hexapod will be built in Solidworks and exported to a suitable simulation package for simulation and testing. There have been some previous comparison surveys of current simulation software – both commercial and open source - available for robotic platform simulations (Kumar 2011, Staranowicz & Mariottini, 2009), however as this is a constantly expanding field, these surveys cannot be taken as being comprehensive. After reviewing the comparison papers mentioned, and conducting further online research, four software packages were selected for more detailed comparison in order to decide on the best option for this project. The final short list of simulation packages which were considered are MRDS, Morse, Gazebo, Webots and V-Rep.

Microsoft Robotic Developer Studio

MRDS is a free, full featured 3D Robotic Simulation environments developed by Microsoft. It is available for Windows, and is compatible with C#, Java, or their own, proprietorial Visual Programming Language. It is designed with an easy to use GUI and is meant to be accessible for hobbyists with limited programming experience. For simulation, MRDS uses NVIDIA PHYSX technology.

While MRDS presents itself as accessible and easy to use, it is limited by its dependencies on other Microsoft products – does not seem to offer compatibility with ROS and Python, which are being considered as the favoured programming environment for this project, and appears to be aimed more at the hobbyist market (Microsoft 2014).

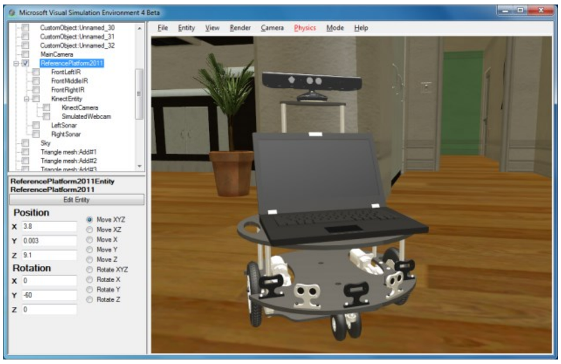

Figure 8: MRDS Screenshot (Microsoft 2014)

Morse

The Modular Open Robotic Simulation Engine, or MORSE is built on Blender, the Bullet physics engine and Python, and is controlled almost entirely from the Command Line. Morse comes with a number of predefined environments from small to large, indoor and outdoor, a range of standard sensors and a selection of prebuilt robot platforms, with the ability to import others. Morse is only available on Linux Ubuntu, and supports the Robot Operating System (ROS). Morse does not have any embedded advanced algorithms, such as path planning, and its producers state that it cannot be considered to be physically accurate for fine motor functions in its current version (1.2.1) (Open Robots 2014)

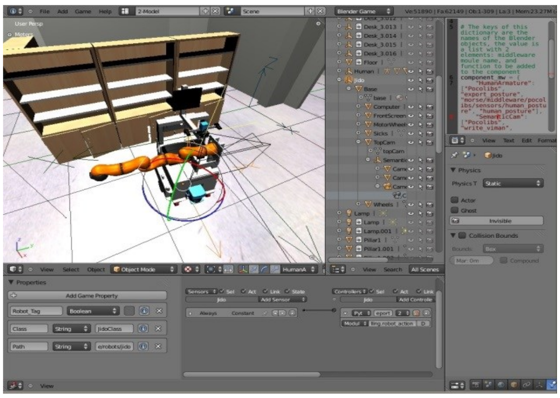

Figure 9: Morse Screenshot (LAAS-CRNS 2014)

Webots

Webots is a popular, full featured, Swiss developed 3D simulation platform used by over 1000 universities and research institutes globally. It features a library of prebuilt examples and environment, as well as extensive sensor and actuator libraries and an intuitive GUI and programming interface. Webots uses the Open Dynamics Engine (ODE) physics library, and the professional release allows for additional physics engine plug ins. Webots is available for Window, Mac OSX and Linux, and allows for programming robots in C, C++, Python, MATLAB, Java and ROS (Cyberbotics, 2014).

Webots was the simulator used by Matt Denton, who designed the Mantis Walking Machine – currently one of the largest functioning hexapod walking platforms (Denton, 2014). However the full featured version of Webots is not cheap, at $US 2300 for the Academic discounted Pro version, and the Educational version, which is lacking the additional Physics plugin, Supervisorial programming and Fast Simulator Mode, is still $US 350 for a licence (Cyberbotics, 2014). Matt Denton also indicated that Webots was computationally demanding, and ran best on a good quality desktop (Denton 2014 pers. comm. Sept 3).

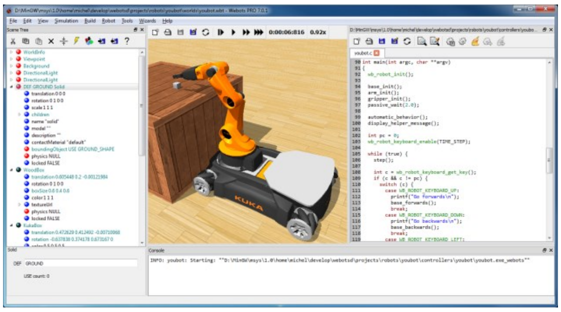

Figure 10: Webots Screenshot (Cyberbotics 2014)

Gazebo

Gazebo is a free, open source robotic 3D simulation platform that is heavily integrated with the Robot Operating System (ROS), and is currently only available for Linux Debian. The current version of Gazebo (4.0.0) utilizes the Open Graphics Rendering Engine (OGRE) for 3D modelling and rendering, as access to a number of physics engines – namely ODE, Bullet, Simbody and Dynamic Animation Robotic Toolkit (DART) – all of which are high performance open source physics engines. Gazebo allows you to simulate sensor data from a wide range of sensors, comes with a number of pre packed robot models or allows you to import your own model, and allows for programming in C, C++, Java, ROS and Python, with some plugins available for other languages such as Java. Gazebo has a GUI, but seems to favour its Command Line Tool, making for a less intuitive environment for the first time user (Open Source Robotics Foundation, 2014). Gazebo is the simulation Software recommended in conjunction with ROS in the Darpa Robotic Challenge (Ackerman 2012).

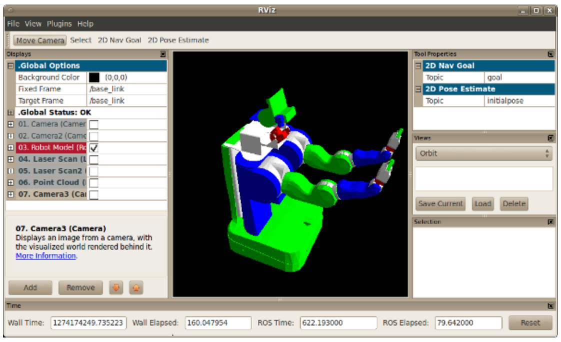

Figure 11: Gazebo screenshot (Gazebo.org, 2014)

V-Rep

Virtual Robot Experimentation Platform, or V-Rep is a commercial 3D robotic simulation package that uses some open source modules. V-Rep offers a full featured Educational licence, which differs only from the Professional version in that it is watermarked. It is available for Windows, Linux and OSX. V-Rep comes with an easy to use, intuitive GUI, and a large range of pre packed models, as well being able to easily import and define 3D models from other CAD programs. V-Rep has a range of configurable sensors and actuators, and uses the open source ODE, Bullet and Vortex Physics Engines. V-Rep has a very versatile API, allowing for six different programming approaches – embedded scripts, add-ons, plugins, remote API, ROS nodes and Custom Client/Server – and is compatible with a range of programming languages; C, C++, Java, Python, Lua, Matlab, ROS, Octave and Urbi. V-Rep also has comprehensive motion planning, Data and Visualisation recording and exporting, inverse and forward kinematic calculations, and allows for easy editing of models within the simulator, and many other features besides.

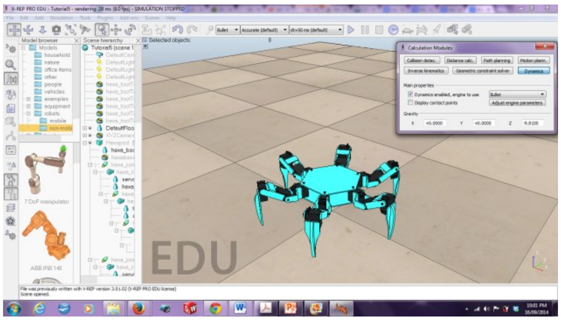

Figure 12: V-Rep Screenshot (Copelia Robotics, 2014)

After reviewing the available platforms, V-Rep was chosen as the software of choice for simulation as it was the best choice for versatility, range of tools, language compatibility, ease of use and cost effectiveness.

Prototype Platform

Hydraulic Powered Large Platform

Some initial costing has been done to investigate the feasibility of building a large scale hydraulically actuated robotic platform. Much of the basis of this investigation used the system optimisation research conducted for the Comet IV hexapod project (Nonami et al 2014).

Electromechanically, such a platform would consist of: A combustion engine power supply and fuel tank (a high torque V twin motorcycle engine of around 500 – 700CC was considered); a split system hydraulic pump and oil reservoir, for an optimised system able to provide high torque for the stance phase and high flow for the swing phase of leg actuation – a unit that could supply a flow rate 80 l/m and 2500psi of pressure was considered for initial modelling; A DC power alternator, battery energy storage and power supply and regulator for electrical and electronic components; Hydraulic actuators – 18 of, a bore size of 50 – 75mm, rod diameter of 25 – 35mm and stroke length of 280mm – 350mm were considered for the two non-shoulder leg joints – suitable units were available from various suppliers for around $100 per piece; 18 electric over hydraulic proportional/directional control valves ; Hydraulic hoses and fittings; sensors etc; mechanical components such as bearings for leg joints; control architecture – microprocessors for individual component control and reflex architecture and CPU for higher level control, data processing and decision making.

In general, the hydraulic components were costly throughout – especially given the multiple items needed for an 18DOF actuated mobile robotic walking platform.

Figure 13: HAWE PSV valves (Advanced Fluid Systems, 2014)

The most cost prohibitive item out of the hydraulic components is the proportional/directional control valves. Of the larger, hydraulic actuated platforms already in operation, the Comet IV uses HAWE PSV 3S1 proportional valves with HAWE PLVC4 drivers (Nonami et al 2014), while the Mantis Walking Machine (Denton, 2014 pers. comm. Sept. 3) used Rexroth Bosch 4WREE Proportional type valves. A couple of Hydraulic companies (Hanson Hydraulics 2014 pers. comm. Aug. 20), special effects companies (Dan Olivers FX, Creature Technology Company, 2014 pers. comm. Aug. 20) and Asia based hydraulic component suppliers (Alibaba.com 2014 pers. comm. Through August) were also contacted for advice and quotes. The quotes for the required stackable proportional hydraulic valves ranged from $1100 (Alibaba.com, 2014 pers. comm. Through August) per unit to ~$6000 (Hanson Hydraulics 2014 pers. comm. Aug. 20) per unit. A more cost effective approach of using a proportional pilot on a directional valve was also investigated (Alibaba.com 2014 pers. comm. Through August) – this brought the cost per unit down to around $350 each, but had the drawback of making the hydraulic circuitry more complex, requiring more components and fittings and therefore less cost effective and efficient – and in being less stackable were bulkier and would increase the overall weight of the platform.

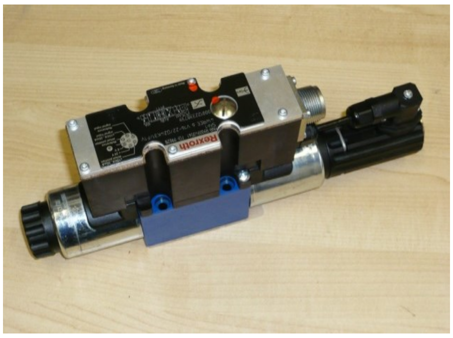

Figure 14: Rexroth Bosch 4WREE valve (Mantis Robot 2014)

From these initial investigations, the estimated weight of the platform being considered would be in the range of 750kg – 1000kg, and the material costs would be anywhere in the range of $14,000 to $44,000 depending on the valve control solution decided on (Though this could even be as high as $120,000, if the high end, $6000 valves were desired). Obviously, even at the lower end of this price range, this is neither practical nor feasible for this current investigation. Therefore a more modest and practical scaled prototype, using servo motor actuation and an aluminium body will be built in order to test the control system and navigation algorithms.

Prototype Methodology

The design of the prototype platform will be designed and scaled in part from the earlier research in to leg design and kinematics, and in part dictated by the availability and affordability of the components. Servo motors with a maximum torque of 15cm.kg seem to be the limit of what is readily available before the unit cost increases significantly (hobbyking.com 2014), so the platform will most probably be designed around what these units are reasonably capable of. The prototype will be of a scale of approximately 300mm – 500mm diameter – though this may be subject to change as the design process is defined. It will most likely be tethered, as power and payload restrictions are of less of a concern, as the purpose of the platform is to test the performance of control systems, reflex networks and navigation algorithms intended for larger platforms.

Control System and Coding

A number of hardware platforms have been investigated for the control system of the prototype hexapod – both microprocessors for the reflex leg control, and possible CPU's for higher functions and SLAM processing.

Arduino

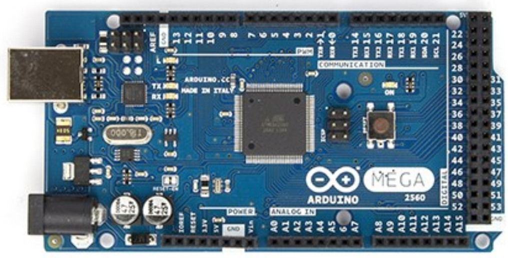

Figure 15: Arduino Mega 2560 Development Board (Arduino 2014)

The Arduino chip is based on the AVR family of microprocessors, but with the Arduino Integrated Development Environment (IDE), which is easier to use, more intuitive and more versatile than the Atmel C compiler. Arduino also has an extensive online community, with many open source code snippets and libraries available to fulfil a wide range of functions – this can greatly speed up development time for new and complex problems, as there is no need to reinvent the wheel each time. There is also extensive hardware support for the Arduino, with many shields on the market to accommodate a wide range of peripheral hardware.

The Arduino Mega 2560 is built on the ATMega 2560 8 bit chip, has 54 digital I/O's of which 15 can function as PWM outputs, 16 Analog inputs, a 16MHz crystal oscillator, 256 KB of Flash memory, 8 KB of SRAM and 4 KB of EEPROM (Arduino 2014).

Parallax Propeller

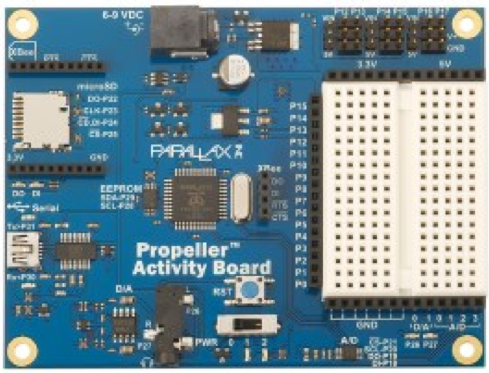

Figure 16: Parallax Propeller Activity Board (Parallax 2014)

Parallax have been producers of microprocessors popular with mechatronics engineers for more than 20 years, being the manufacturer of the BASIC 1 Stamp chip, and are involved in a collaboration with Microsoft Robotics to develop a robotic learning platform incorporating Microsoft's MRDS and the Kinect as a visual sensor system.

Their current flagship microprocessor is the Parallax Propellor P8X32A processor – a 32 bit, 8 core parallel processor, with 64KB of ROM/RAM. The chip operates with a clock speed of up to 80MHz and is programmable with Parallax Assembly, Spin – an object based higher level language that is proprietorial to Parallax, or C/C++. The chip has 18 multi-purpose I/O pins. The developer kit also features an X-Bee port for wireless communication, a micro SD card slot for flash drive expansion and 2 channel D/A and A/D conversion. A custom board is also available that permits interfacing with Arduino hardware shields (Parallax 2014).

While having less I/O pins than the Arduino, a less familiar IDE, and less comprehensive online community, therefor less programming resources, the multicore parallel processing capability make it a string choice for this particular application.

Raspberry Pi & Beagle Board

Figure 17: Beagle Bone Development Board (beagleboard.org 2014)

Raspberry Pi and Beagle Board are two more 32 bit, ARM based Microcomputers, each with ~40 GPIO's. The Beagle Boards ARM Cortex A8 processor is superior to the Raspberry P's ARM 11 – reportedly capable of twice the executable commands per clock cycle (Texas Instruments 2014).

The Raspberry Pi has twice the RAM of the Beagle Board, and both have expandable flash memory with an SD card slot. Both run a Linux operating system, and both support various development languages including C++ and Python, and both are optimised for video processing, which will be advantageous for SLAM applications. The Raspberry Pi, retailing at around $50, is the more economical option than the Beagle Board at around $90 (raspberrypi.org, beagleboard.org 2014)

Intel Edison

Figure 18: Intel Edison Developers Board (Intel 2014)

The Intel Edison is a very recent product on the market from Intel, an is a low power, compact 32 bit processor that uses a dual core, dual threaded Intel Atom CPU at 500MHz and a 32-bit Intel Quark microcontroller at 100 MHz. It has 40 GPIO's, 1GB RAM and 4 GB of flash memory. It supports development with C, C++, Arduino IDE, with Python, RTOS and C# pending. It is also available on a couple of breakout boards including an Arduino Uno compatible one. It is priced competitively (~$50) with the other microprocessor options available, while offering considerably increased processing power (Intel 2014).

The Edison is a very new product so the online resources currently available are limited, but this compact, powerful and versatile unit offers microcomputer capabilities in a microprocessor environment, so is a very attractive option for the main CPU for the Hexapod.

No definite decision on the CPU/Microprocessor to be used for this project has been made at the time of writing, but the Intel Edison or the Beagle Bone are front runners, possibly using the Parallax Propeller for addition, lower level control.

Python

Python has been selected as the language for programming the higher level functions in this project, as it is designed to be easy to use with a simplified syndic compared to languages such as C++, is multipurpose, but popular for AI and engineering applications, supports multiple programming paradigms such as object-oriented, imperative and functional programming or procedural styles. Has an extensive standard library, with a large online community with plenty of more specialised open source libraries available (Python Software Foundation 2014). Python is also supported by the Robot Operating System (ROS).

Robot Operating System (ROS)

For this project, the aim is to implement the Robot Operating System (ROS) to build the control environment.

ROS is and open source project that consists of a collection of flexible frameworks, incorporating tools, libraries and conventions for building robust and adaptable software. It is designed to work on computer clusters, is modular, includes hardware abstraction and has extensive libraries to suit a wide range of robotic functions including visual systems using either digital cameras or Kinect, inverse kinematics, path planning, SLAM, face and gesture recognition and many more besides. ROS is supported by V-Rep and supports Python, and ideally needs to run on Linux Ubuntu. In all ROS seems like a powerful set of tools and ideally suited to this application (Open Source Robotics Foundation 2014) ROS is also the favoured framework for the DARPA Robot Challenge (Ackerman 2012).

Conclusion

Designing and building a functional multipedal autonomous robotic platform, that is of a practical scale, with multiple DOF's in each leg, that can operate at reasonable speeds in an unstructured environment is a complex and multi layered process. It is the intention of this project to examine these issues and formulate a scalable design process, while building a functional testbed for developing the SLAM, control and navigation architecture.

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Preliminary Timeline