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Bionic Limb Mechanism and Multi-Sensing Control for Cockroach Robots

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1. Introduction

In the past twenty years, robotics has undergone rapid development. Through the usage of new technologies and new materials, robots have found widespread applications in a variety of industry sectors. In contrast to traditional robots, a new branch of biologically inspired robots has emerged strongly. By studying biological systems like insects, robotics researchers strive to seek in-depth understanding of different kinds of bionic movement phenomena that exist in nature.

The rolling of a wheel is regarded as a mode of motion with supreme efficiency, but it is only suitable for robot to move on a flat surface. Leg type locomotion is much more desired for a robot to transverse on a rugged topography, and is considered more superior than wheel type in rough terrain. Leg type is a common movement in nature, from human to insects, with similar walking modes. These biological systems do not roll, but have biped or myriapod alternate walk. In recent years, robotics researchers have shown special interests in insects, hoping to understand the mechanisms of leg type movement and its superior motion on rough terrains as opposed to wheel type movement.

It is found that when running on a complex terrain, animals can adjust themselves to disturbances (Karalarli et al, 2004). This is hard for robot that walks with wheels to realize. In the dire situation of being caught, insects run away very swiftly to escape from the danger. They have extraordinary motion agility. A cockroach can run one step in 50 ms or at a velocity of 20cm/s. It can jump over an obstacle that is as high is as three times of its stature, without slowing down. It spooks quickly with very little response time.

Cockroaches can move and run swiftly and smoothly no matter what terrains to transverse. Their movement smoothness, flexible self-control, and regulation ability have aroused researchers' deep interests to seek the secret of the movement. Cockroach's control over its agile movement far exceeds high speed computer control in terms of response time and control functions. Scientists have failed to find satisfactory explanation about cockroach's supreme performance and control ability in adverse conditions. It is foreseen that overcoming this difficulty will be an important breakthrough for many correlative subjects, lead to the emergence of new research methods, and promote the development of intelligent robot technology to the benefit of humankind.

Bionic cockroach robots can be applied broadly to earthquake relief, riot, search and rescue, and space exploration in rugged and unstructured natural terrain. Cockroach's quick reflection and dodge mechanism can be applied to aeroplane collision avoidance. To bring biorobots a step closer to real applications, novel locomotion mechanism, multi-sensor information processing and fusion, and intelligent control must be thoroughly investigated to emulate cockroach's moving rapidity, flexibility and stability. Cockroach limb is intriguing, and has calculation function and local intelligence. Intensive research is required to mimic the mechanism configuration and physiological characteristics of insect limb.
A collaborative research project between Beijing University of Aeronautics and Astronautics and the University of Canterbury has been launched to improve bionic robot's movement mobility and intelligent control level through multi-sensor fusion. It explores all-weather vision sensor, head palp and leg feathers based on fibre optic and tactile sensing; and studied multi-sensor information processing and fusion in depth for the realization of cockroach robot's intelligent control. It proposes Backstepping disperse adaptive control scheme based on robust information filter to solve control difficulty caused by nonlinear system modelling error, and disturbance factors. Correlative theory of bionic cockroach robot and its application features contribute towards the development of biorobot control theory and application fields in the field of bionic robotics.
This paper firstly gives a brief overview of bionic cockroach robots that have been developed in the past decades. It then discusses the design of bionic mechanism using parallel kinematics and spring joints in offering a realisable approach to emulate the functions of cockroach legs. It is followed by proposed schemes on all-weather vision system and tactile system. It further proposes a distributed multi-CAN bus-mastering system based on FPGA (domain Programmable Gate Array) and ARM (Advanced RISC Machine) microprocessor, and FPGA-based motion control. Finally conclusions are drawn.

2. Overview of Bionic Cockroach Robots

A cockroach has an effective formation of six legs that accomplish complex movements regardless of terrain conditions, as shown in Fig. 1. In rapid movement, the front and hind legs of one side and middle leg of the other side forms a group. As a result, three points distribution ensures excellent movement stability (Bai et al, 2000).

Fig. 1. Cockroach with six legs spreading out.

Biologists at the University of California at Berkeley have experimented on cockroach's adjustment to external disturbances. A very small cannon was fixed to a cockroach. A lateral thrust with a duration of 10 milliseconds is exerted to the cockroach using recoil of cannon.

It was found that this cockroach had adjusted its body balance well before taking the next new step. It turns out that a cockroach has control balance ability that far exceeds high speed computer control. So far, researchers struggle to find a satisfactory scientific explanation about cockroach's such natural ability. Many multidisciplinary difficult issues involved in the bionics study leads to wild science fascination, and bionic robotics has become an emerging research subject that deserves in-depth exploration.

In the past bionicst had attempted to develop new fashioned vehicles to achieve agile motion on rough terrains by studying cockroach locomotion. At the same time, biologists were intrigued by neural network of cockroach's nervous system which works very effectively despite its simple structure. In September 2004, The National Science Foundation (NSF) announced a $5 million, five-year grant to the University of California, Berkeley. The grant funds biologists, engineers and mathematicians from universities across the country to try to understand the mechanical and neurological basis of locomotion. This signifies an important effort in search of in-depth understanding of cockroach locomotion and its intelligence.

Owing to the special features of cockroach, in recent years robotics academics have devoted intensive research effort to the development of cockroach robot. Based on the development in the past decades, cockroach robots can be roughly categorised into three types. The first type is "Robot" series, shown in Fig. 2.

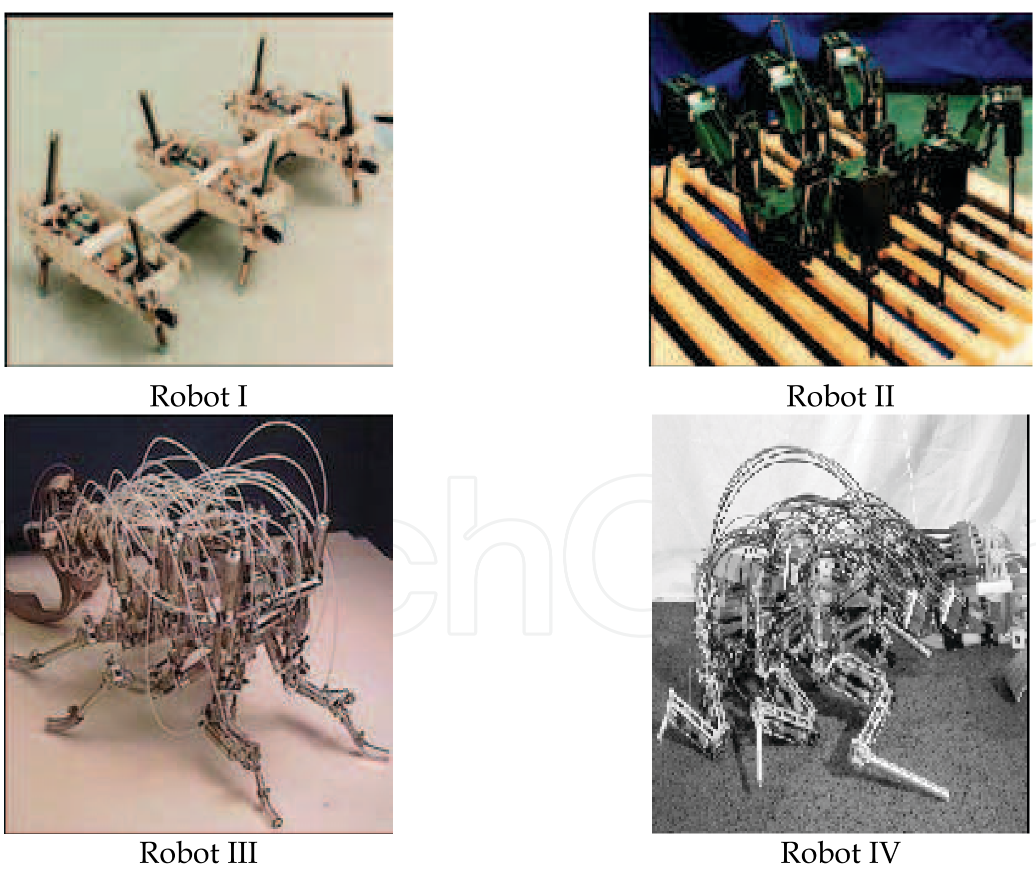

Fig. 2. Robot series of cockroach robots

In this series, the contour design, developed by Case Western Reserve University, has features of bionic mechanism. Its first generation prototype Robot I is made of six legs of

two degrees of freedom (DOF) and driven by Direct Current (DC) motors. It has a bionic neural network controller. In the second generation prototype Robot II, each leg has 3 DOF. The robot adopts a distributed control system to achieve harmonious motion of legs and insect gait. Robot's physical height and orientation are taken charge by a central controller. In the third generation prototype Robot III, the number of degrees of freedom is distributed among the six legs unequally. There are a total of 24 DOF, with each of two front legs having 5-DOF, middle leg 4-DOF, and hind leg 3-DOF. Furthermore, pneumatic drives are employed to obtain a larger explosive force. Such design makes front leg most agile, and the leg has guiding and sensor function. Middle leg is agile enough to hold up and turn the robot. Hind leg is least agile, and is provided with a strong propulsive force. (Quinn & Ritzmann, 1998). The fourth generation prototype Robot IV is based on Robot III, and uses artificial muscle to approach biologic bionics (Quinn et al, 2003).
The second type of cockroach robots is represented by Whegs that is also developed by Case Western Reserve University. The Whegs series of cockroach robots is shown in Fig. 3. The contour design does not follow cockroach's bionic mechanism. Instead it takes advantage of both wheel type movement and leg type movement, then abstracts features of cockroach movement to carry out mechanism design and function simulation (Schroer et al, 2004; Quinn et al, 2004). Whegs robot is thus based on abstract biology theory (Allen et al, 2003). In Whegs I, each leg has only one rotational DOF for wheel type movement. It is built with a tri-spoke structure which allows for movement on rugged road. Whegs II can bend its body to have better movement agility than Whegs I. Whegs III's structure has the feature of micro motion and it has only four tri-spokes instead of six. The terminal of its tri-spoke has barbs which facilitate wall climbing and moving on rugged road. Whegs IV is similar to Whegs II, but it does not have flexible joint as in Whegs II. Its main improvement is that its tri-spoke structure has flexibility and compliance, which benefits transversal motion.

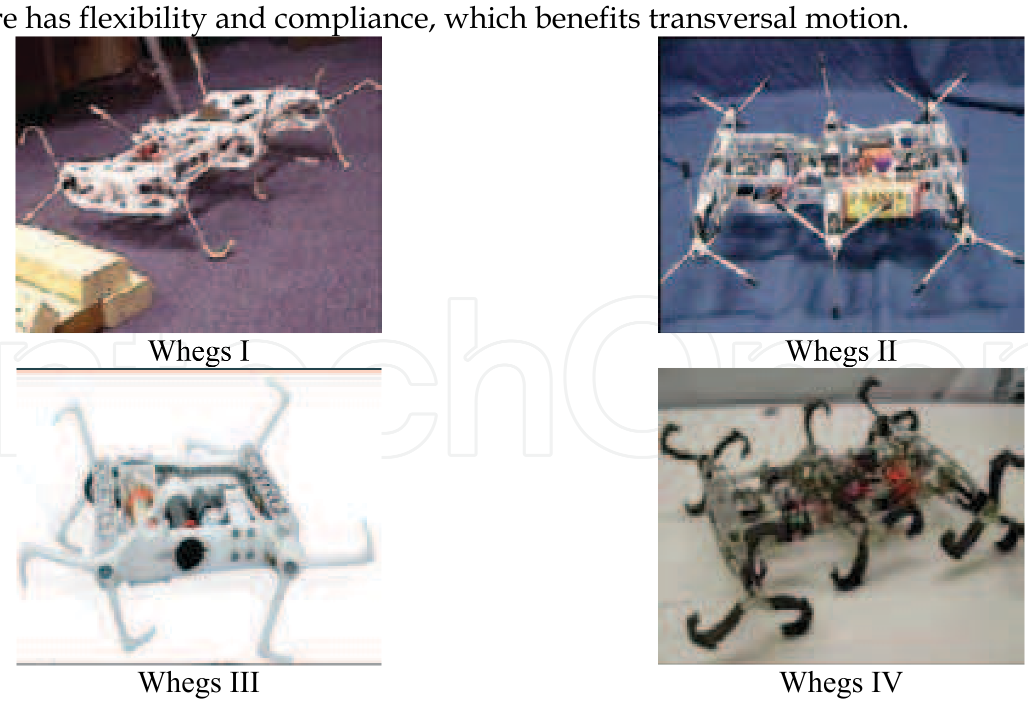

Fig. 3. Whegs series of cockroach robots

The third type of cockroach robots is RHex, developed by University of Michigan, UC Berkeley and McGill University. Fig. 4 shows the prototypes developed through different stages of development. RHex is similar to Whegs in that 6-DOF bionic cockroach movement is achieved based on abstract biology theory (Sarandli et al, 2000). The first generation prototype Rhex 0.0 was developed in 1999. Then Rhex 0.1 and RHex 0.2 were improvements on RHex 0.0. The improvement of RHex 0.1 is mainly the mechanism, resulting in a 10% weight reduction. Rhex 0.2 incorporates tactile sensors to detect surrounding environment (Moore et al, 2002; Komsuglu et al, 2001). In recent years, controller with gait adaptive algorithm further enhances function of RHex (Weingarten, 2004).

RHex 0.1 RHex

Fig. 4. RHex series cockroach robot

Case Western Reserve University has further studied cockroach's mechanical structure, and developed MechaRoach. The robot walking and wall climbing functions are built according to the mode of cockroach's bionic motion (Wei et al, 2004). Fig. 5(b) compares the leg structure of MechaRoach with a biologic cockroach in different scale factors. Different from Robot series mechanism bionics, MechaRoach has only one initiative joint in each leg, and it realizes mechanism bionics through crank rocker (Boggess, 2004). Such motion function is not as versatile as those in the previous three types of cockroach robots.

(a) MechaRoach (b) Comparison of legs structure

Fig. 5. MechaRoach cockroach robot

Currently the research focus of cockroach robot is mainly on motion agility and smoothness control. As far as leg mechanism is concerned, bionics research mostly deals with simulation of cockroach leg structure topology that treats hip joint, knee joint and ankle joint as serial mechanism. Latest human bionics analysis manifests that human shoulder joint movement depends on muscular cable-driven to drive joints. Such cable drive is an inter-coupled parallel mechanism linking shoulder, elbow and wrist, as shown in Fig. 6.

Fig. 6. Sketch of human arm drive

It is found from the structural analysis of cockroach leg that Cockroach motion control is accomplished by a parallel structure. What impact does a parallel structure have on cockroach's motion state? Does it help cockroach's stability of motion, load capacity and skip ability? Does it cause adverse impact on velocity of movement? Discovering these answers may provide new clues for humans to explore the secret of cockroach motion ability. In this regard, developing parallel mechanism to emulate cockroach leg has become an important premise for cockroach motion control.

Conventionally robot links and joints are rigid. But biologic limbs and joints are flexible. Cockroach leg's flexibility provides spontaneous regulation of movement stability with little computation in the brain. Hence, constructing cockroach legs with flexible materials to emulate the bionic functions is indeed a significant step towards bionic legs. So far, there have been reports about using insulation elastomer man-made muscle driver (Kornblush et al, 2002). Although flexible material brings benefits to motion stability, it faces some practical difficulties in motion control.

Cockroach has superior movement adaptability to differtent terrain conditions. Such mobility is attributable to two bionics aspects: i) cockroach body and legs distribution of structure, and ii) fast sensor information processing capacity and virtual intelligent control. In the latter, touch and vision sensing plays an important role in realizing the intelligent motion control, and hence requires in-depth research. In addition, sensor information processing empowered by real-time computation and multi-sensor information fusion allows a cockroach robot to perceive its operational environment responsively and accurately. These two aspects of sensing and information processing are challenges that must be overcome to mimic bionic operations of a cockroach.

Although robotic vision has been widely used in a controlled environment, how to make it adaptable to varying and unknown environments remains to be a challenge. Human visual system is highly robust, and removes redundant information and extracts useful information that is related to current visual behavior from profuse visual information. As an illustration, once fixing their point of attention to an object, eyes follow the moving object so that the object is imaged in the central fovea (sharp image) all the time. When the object exceeds the physiologic limit that eyeball can turn, human will resort to head, even body's turn to follow the object and obtain a clear image as far as possible.

When humans observe a scene, eyes often focus on some characteristic points of the scene. Fourier spectrums of these characteristic points contain many high frequency components and amounts of information. If we can control eyes and make eyes fix on the goal of interest, then the speed of image processing can be enhanced greatly. For a complex system that contains multi-sensor information, owing to modeling error, external disturbance, load fluctuation and temporary set causing position error, state space variables are inter-coupled. Consequently it is very challenging to design realizable filter and controller in system state space. Effective methods have to be devised to realize multi-sensor information processing, hence intelligent motion control.

Although a cockroach has agile movement, its nervous system is very simple (Beer et al, 1997). The limited capacity of the simple neural network shows that the nerve centre does not take care of everything itself, and that each leg's movement is self-controlled by each leg's controller. It is therefore suggested that cockroach robot control system should adopt principal and subordinate distributed control structure (Espenschied, 1996). Master controller of brain level allocates task for each master controller of leg level based on programming task requirement. Master controller of leg level sends commands to its subordinate controllers which are the individual joint controllers. There are information alternations between principal and subordinate controllers to realize intelligent motion control. Control algorithms should be simplified to accelerate controller's operational speed.

Cockroach robot has more than 10 years research history, but it is still in its infancy. In the ongoing project, the concept of region control has been proposed. It is designed to substitute routine point control scheme. Region control has many examples in life, such as chess player placing chessman. Players do not need to place chessman in the decussate point exactly, but a region near the ideal point. It is obvious that the point is the limit of region and reducing the region leads to the point. Intuitively it can be concluded from the problem of placing chessman that region control is easier than point control and requires much less computational time. The velocity of body's movement using region control can be faster. Ascertaining the size of the region of interest based on task requirements helps a cockroach robot achieve movement rapidity and flexibility.

3. Design of Bionic Limb for Smooth Motion

3.1 Multi-Discipline Fusion Approach

In the multi-discipline fusion approach, bionics, mechanism and disperse adaptive control theory are combined to realize harmonious development of bionic mechanism and modern control theory. Preliminary research indicates that dynamics characteristic of organism incarnates bionic dispersed intelligence. Disperse adaptive control theory and technology, which studies bionic mechanisms, extends biologic dispersed intelligence to artificial intelligence. Multi-discipline fusion approach offsets single subject’s difficulty caused by limitation of technology. Combining cockroach robot’s leg configuration and calculation function draws the knowledge from math, mechanics, mechanism, artificial intelligence, electronics and control theory.

Bionic cockroach robot can be viewed as an integrated sensing, opto-electro-mechanical (OEM) system with real time adaptive control. Such an OEM system should have small volume, high precision and good real-time performance. Commercial sensors like mechanical sensors and light frequency and phase modulation sensors cannot be easily deployed in bionic limb design due to the volume factor. Electric and magnetic sensors are small and sensitive, but have limitations in reliability and anti-interference electromagnetism stability. Especially for a cockroach robot, its figure should be gracile, and be easily integrated in arrays. Such a robot should have good dynamic response, high sensitivity and strong anti-interference electromagnetism ability. Based on synthesizing all factors, differential light intensity modulation fibre optic sensor becomes a preferred sensor of the cockroach robot sensor system.

3.2 Biomimetics Approach

Bionic cockroach robot can be considered as a parallel mobile robot with six legs. Development of such a robotic system needs to cover robot's configuration design to achieve dexterous movement; and modelling and dynamics control of a cockroach robot with optimal configuration. This work aims to analyze existing techniques in design of parallel kinematic machines, and conduct fundamental research and innovative mechanism design to achieve motion smoothness in cockroach robots.

In consideration of joint drives of hip, knee and ankle moving in partial coupling, configuration design, dexterous workspace, and design fundamental of optimal coupling are to be ascertained. In terms of modelling, kinematics and dynamics control, high redundant arithmetic control and analysis of singularity workspace and control arithmetic of avoiding singularity need to be studied.

In developing a bionic mechanism, optimum coupling design hip, knee and ankle joints, corresponding to the model of system and analysis of movement, is necessary. The core of this problem is to discover the secret of cockroach's movement mobility based on mechanism theory, to study high redundant control arithmetic and mechanism design when being overdriven, and to supply hardware base for the realization of bionic cockroach robot.

In terms of leg mechanism design, two approaches are considered; i) bionics approach, and ii) abstract transplant approach. The base of bionic cockroach robot's mechanism design of hip, knee and ankle comes from illumination of research on hip, knee and ankle joints of cockroach. There are two bionic methods: one is mechanism biomimetics, the other is function biomimetics. Function biomimetics is combined with mechanism biomimetics for the design of cockroach robot's leg configuration. Not only does such a combinatorial design method assimilate the merit that biologic cockroach's limb mechanism possesses movement agility and smoothness, but also overcomes the difficulty that complete imitation of cockroach's structure and functions is impossible because of technological limits.

The abstract transplant approach is to emulate cockroach limb being elastic. It is impossible for a stiff pole to realize limb mobility. While it is difficult to find an elastic material having similar properties to cockroach's limb, limb's local function can be simulated with a spring mechanism which would greatly simplify the leg mechanism design.

Before the detailed design, theoretical analysis of leg mechanism of cockroach robot, kinematics and dynamics modelling are carried out. It is followed by simulation and experimental verification. Verifying the correctness of the theoretical model via simulation can economize time and cost, and is simple and effective. Further experimental studies and prototyping are conducted to validate rationality and correctness of correlative theory and arithmetic, improve the design and reliability, and provide the feedback to refine the theory.

3.3 Design of Bionic Joints

3.3.1 Design of Bionic Hips and Knees

Based on physiological characteristics of cockroach's front, middle and hind legs, the motion feature of each leg is observed. Front leg is deft and mainly used to turn and adjust body pose. Middle leg is swift and mainly serves to hold and turn body. Hind leg is strong and powerful, and drives a cockroach to walk. The mechanisms of front, middle and hind legs are designed differently to suit the motion characteristics. Fig. 7 illustrates front, middle, hind legs structure.

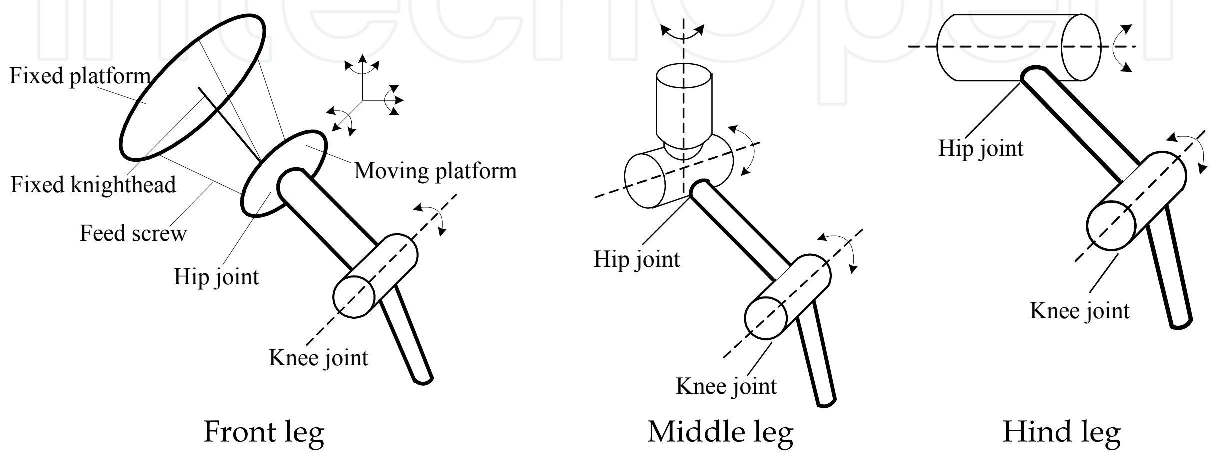

Fig. 7. Structure sketch of cockroach robot's leg

In the front leg, hip joint is designed to be 3-DOF globe joint, and knee joint to be 1-DOF rotary joint. In the middle leg, hip joint is a 2-DOF rotary joint, and knee joint 1-DOF rotary joint. As for the hind leg, hip and knee joint are all designed to be a 1-DOF rotary joint. Ankle joints of all legs are fixed structure. Altogether 18 degrees of freedom are required to realizing cockroach robot's agility function completely. The 3-DOF in the front leg hip joint is important for cockroach robot mobility and terrain adaptation. In this project, the concept of parallel kinematic globe joint is proposed to realise the front leg hip joint.

The concept of globe joint emulates biomimetics exhibited by biological systems. Human hip and shoulder joints are globe joints. They contain all rotational DOF of Euclidean space, and therefore have outstanding movement rapidity and mobility. A common approach in designing bionic leg is that the robot globe joint is approximated by two 2-DOF joints that have two orthogonal axes and the link is constructed as a 1-DOF rotary joint. This work proposes a scheme that realizes globe joint function by three parallel telescopic mechanisms, as shown in Fig. 8.

The drive for the telescopic mechanism may adopt one of three feasible methods, namely, air cylinder, pneumatic artificial muscle and feed screw. In this work, feed screw driven by motor is chosen for its simple motion control.

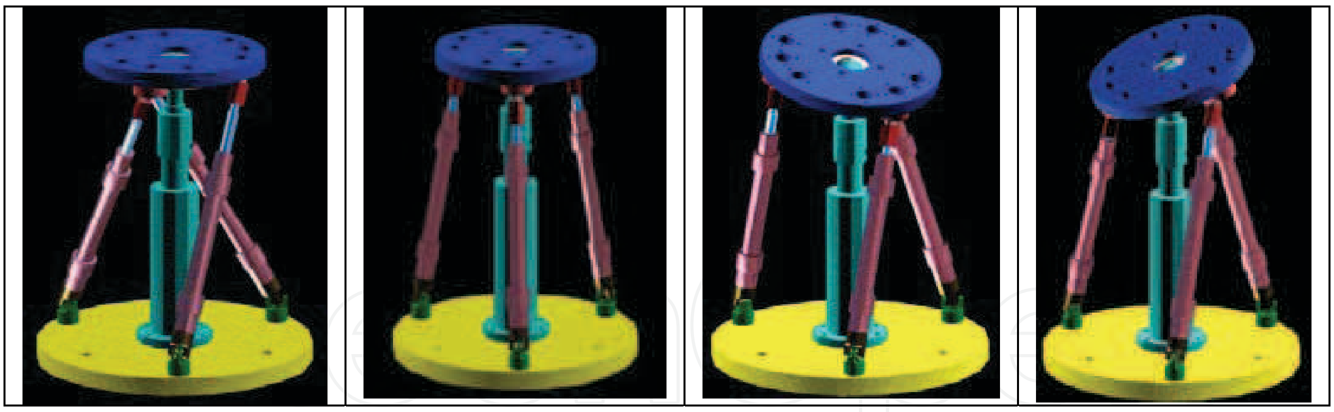

Fig. 8. Sketch of globe joint

3.3.2 Design of Bionic Flexible Joints

Most biological organisms are flexible. It is one of the main reasons why an organism can easily complete all kinds of difficult movements. Such a built-in flexibility in robot joints would allow a robot to move reposefully. For the bionic cockroach robot under development, flexibility is in-built at globe joint and rotary joint. Front leg flexible globe joint, shown in Fig. 8, comprises a moving platform, a fixed platform and four knightheads that connect the two platforms. Moving and fixed platforms are two disks with different diameters. The centres of moving and fixed platforms are connected by an invariable knighthead while the other three knightheads are connected by telescopic feed screws.
Fig. 9 illustrates the single feed screw connection of globe joint. A flexible element is installed between feed screw nut and joint matrix, which makes front leg of cockroach flexible. The parallel link is coupled to the fixed and moving platform through universal joints. Fixed coordinate is placed in triangular centre of lower platform.

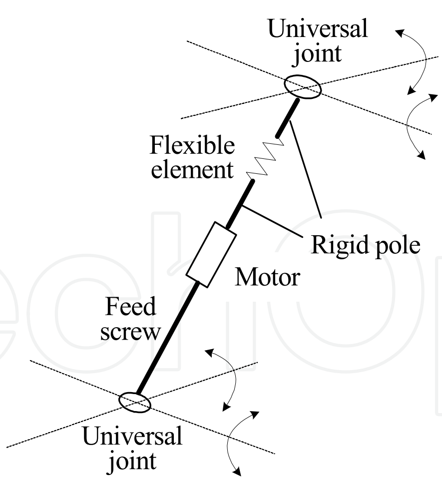

Fig. 9. Design of bionic cockroach robot's flexible joint

The model of universal joint is shown in Fig. 10. The two axes of rotation in the universal joint are two orthogonal axes of the plane that the fixed or moving platform belongs to. The outer ring turns relative to the ground along axis 1, while the inner ring turns relative to outer ring along axis 2. Proper setting of flexible element can be used to fix the other rotational DOF. Elastic material can be used to design the foot, and this will make the bionic robot more adaptable to terrains.

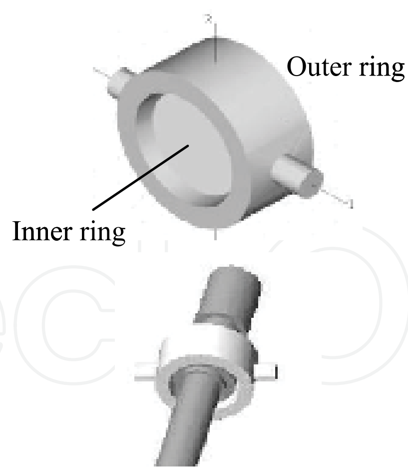

Fig. 10. Globe joint feed screw connection

3.4 Parallel Driver Structure

A driver structure would affect each leg and unitary movement performance of cockroach robot if the coupling between hip and knee joints is weak. Before the design of mechanism, modelling and movement analysis of the bionic system are carried out.
Different mechanism coupling modes are studied by using graph theory.
Change of configuration is analyzed to seek best description method of coupling mechanism, and studied with structurology, kinematics and dynamics.
Universal kinematics and dynamics models containing geometry and movement restriction are established.
The effect of singularity configuration on coupling mechanism form is analysed.
Self-motion manifold under high redundancy condition, and mission-oriented optimal control are formulated.
The dynamical equation for single body is established using the Newton-Euler method. Then multi-body dynamical equation is then established. Constraint counterforce can be eliminated by substitution.
At the initial stage of designing biorobot, 3D robot modelling, dynamic performance and control simulation are integrated using virtual prototyping technology. Firstly, apply modern design theories to biorobot domain and establish 3D dynamic simulation.
Secondly, establish a model to finalise biorobot performance analysis and obtain test data in order to improve biorobot system design performance, economize physical prototype, finalise the design and simulation platform for the design and theoretical analysis of biorobot.
Thirdly, establish mechanical model and dynamical model of the biorobot using virtual prototyping technology. Biorobot overall performance is forecasted, and the feasibility of trajectory is verified. Movement simulation and statics, kinematics and dynamics analysis are carried out to achieve necessary displacement, velocity, acceleration, force and moment curve. As such, optimal joint configuration is obtained, and physical design of the prototype is optimised to improve the overall performance of the biorobot.

4. Multi-Sensing in Bionic Cockroach Robot

A cockroach has an exceptional ability to navigate freely in all-weather conditions. In addition to its visual navigation, it has a powerful detection system built into its legs and feelers to detect its contact states with the environment. These sensing and navigation abilities are important for biologically inspired robot which needs to execute demanding tasks in difficult situations, such as search and rescue, homeland security, logistics in natural disaster, etc.

Multi-sensor information fusion technology is the key to realize intelligent motion control of cockroach robot. To ensure the fidelity of time-dependent sensor information, the information processing has to be carried out in real time. In face of a large amount of information including visual images, the real-time processing becomes very difficult. Cockroach has visual, tactile, taste, smell sense function, etc. For practicality, only visual and tactile sensors are considered at this stage. The vision system mainly utilizes infrared imaging sensors, and the tactile sensing system is built upon optical fibre sensors.

4.1 Development of All-Weather Visual Navigation Systems

4.1.1 Imaging Device

Infrared imaging technology has been widely used for sensing natural environment where a robot operates. For a bionic cockroach robot to emulate its biological counterparts, its visual sensing system must satisfy two requirements, i) real-time binocular stereo image acquisition, and ii) real-time high precision 3D imaging processing and recognition. These would equip the robot with all-weather situational awareness and judgment ability.

Non-scan infrared imaging system and multivariate array infrared detector are able to provide real-time environment image. The fundamental is that infrared radiation power is converted to electrical signal detected by the detector. After being amplified, the signal is converted to a video standard signal. One disadvantage of commonly available infrared imaging devices is that they are large and cumbersome. There is a need to improve on the size of optical lens, develop integrated optics, and subsequently miniaturise the entire imaging system.

4.1.2 Calibration

The calibration process aims to establish the relationship between two views in order to extract 3D visual information about the operating environment. Imaging aberrance presented in real life and caused by lens affects the accuracy of image processing results. Matching of two correlation images in the binocular visual device, and abstraction of image characteristic points require data fusion. The calibration process associates images captured by two video cameras that are unattached, and to abstract common information for restoring the fidelity of imaging information.

4.1.3 Recognition

Identification of image feature points and reconstruction of three-dimensional entity data are the key to the visual navigation ability of a cockroach robot. Changing of actual imaging circumstance will lead to the different imaging effect and excursion of characteristic points in binocular imaging. This would cause the probability problem in truthful identification of image features.

So far there has been no practical system that could recognise natural features in all-weather conditions reliably. Therefore, it is necessary to develop a robust and novel detection algorithm that combines high processing speed and efficiency. Wavelet algorithm can be applied for navigation of mobile robots.

The image recognition involves image segmentation, identification and movement judgment. Optimal internal and external imaging parameters can be solved using Tsai imaging model. At the same time, binocular image matching handles standard imaging template and imaging characteristic points. Then correlation pre-processing of images is carried out to reduce image noise and enhance background contrast.

In the abstraction and identification of image characteristic points, the image processing system adopts the wavelet arithmetic to identify contour objects of obtained visual image. It also recovers object shapes and obtains the 3D shape outline of the object by utilizing binocular visual demarcation and data fusion. It further modifies the current 3D model and obtains the position error and external position error of the object by comparing the preliminary 3D model with the current 3D model obtained from video images. Filtering out the false characteristic points, true characteristic points based on current 3D model can be obtained.

4.2 Development of Novel Tactile System

Cockroach's powerful sensing abilities are further enhanced through its tactile perception (leg pressure sensing) of the environment. Indirectly a cockroach senses the leg velocity, high-frequency vibration, surrounding wind velocity, contact softness, ground condition, obstacles, etc. At present there is not much research work that studies the function of fuzz in cockroach's limb. To emulate some of the tactile abilities of a biological system, a highly integrated tactile system with good stability and high precision need to be developed to satisfy the navigations needs of cockroach robot.

4.2.1 Fibre Optic Sensing for Cockroach Robot Tentacles

Fibre optic sensors are identified as a potentially suitable candidate to emulate the sensing functions of cockroach leg feathers and head tentacles. Light intensity modulated fibre optic sensor has small volume, high precision and real-time characteristics. Considering the fine structure of cockroach leg feathers, supersensitive light intensity modulated fibre optic sensors are deployed. The sensing system collects real-time data of pressure, vibration, direction of wind and contact softness, which are produced by the robot's leg movement and its contact with the environment. Composite signal is obtained using optical fibre array. Through multi-path signal processing based on difference measurement step by step, environmental information can be extracted and situational awareness can be achieved.

To mimick the function of cockroach head tentacles, high strength optical fibre is adopted. Changes of light intensity caused by the change of external pressure, wind direction and vibration are thus detected in real time. These physical changes are converted to electronic signals which can be processed internally using photoelectricity transition array. Besides tactile sensor, head tentacles incorporates non-contact near-infrared ranging sensor to enhance the robustness of locating objects and detecting obstacles in a poor visual environment. This sensing approach adopts a specific type of bismuthate optic fibre which is controllable and has near infrared high degree of transparency to guide and focalize light. Thereby suitable ranging position can be selected by changing the position of the head of optic fibre. For illuminant and photosignal transition devices, integrated near infrared semiconductor illuminant, which has a high contrast from background environment light, and photoelectric conversion semiconductor array are chosen respectively.

4.2.2 Cockroach Robot's Tactile System - Leg Feathers and Head Palp

Inspired from tentacles of rodents, a tentacle sensor based on the Position Sensitive Detector (PSD) and Laser Diode (LD) has been designed. The sensor uses PSD as the sensing element; and LD as the incidence light source. The sensor has certain advantages including compact structure; light weight; and ease of processing, assembling, and debugging.

The 2D PSD element, measured 3 mm × 3 mm, can detect the rotation displacement and direction of tentacle simultaneously. To be able to detect texture and roughness of an object in contact, the tentacle of the sensor is designed to be thin poles made of flexible material of 9 ~ 15 cm in length. A light-shading film is fixed near the root of the tentacle, about 2 ~ 3 mm away from the root, In addition, a small hole with a diameter of 0.8 ~ 1.2 mm is opened from the film to receive the light from LD. Through this mechanical design, the tentacle automatically returns to its initial position if it is not in contact with the object to be measured. In a sense, the flexible element resets tentacle.

The PSD is installed on the side opposite the LD. Therefore the sensor can detect the root displacement of tentacle forming on the X-axis and Y-axis of light-shading film. As a result, a voltage signal is output, representing the mechanical displacement of the root of tentacle caused by the bending of the tentacle.

If the tentacle is in contact with an object, a bending deformation is produced on the tentacle. The deformation force causes the movement of the light-shading film fixed on the root of tentacle. As a result, the location of the incidence light spot irradiating onto the photosensitive surface of PSD changes, and the PSD produces an increase in current which represents the change of displacement and direction of the tentacle. By converting current to voltage in the signal conditioning circuit of PSD, a corresponding voltage increment is taken. Then data collection and processing can be carried out to calculate the tentacle movement.

5. FPGA-Based Information Processing and Motion Control

5.1 Control system based on FPGA and ARM

Field Programmable Gate Array (FPGA), essentially logic cells, facilitates real-time processing and control arithmetic of tactile and visual multi-sensor information. Multi-heterogeneity FPGA combines a large number of FPGAs taking charge of different tasks. These tasks include central processing unit in charge of operation, data collection, logic management, etc. The distribution and scheduling of the tasks have great effect on the speed of FPGA.

The control system hardware structure comprises three core parts: Advanced RISC Machine (ARM) processor, distributed multi-CAN bus-mastering system based on FPGA, and CAN bus controller and CAN bus servo driver which controls robot joints. The architecture provides stage treatment for control information and real-time servo control. It solves multi-joint coordinated control of bionic cockroach robot joints, and effectively reduces requirements for bus bandwidth in the networked control system.

The core of FPGA integrates multi-CAN bus controller utilizing System on Programmable Chip (SOPC) technology. Each CAN bus is connected with 3~5 control nodes according to load requirement. Control nodes are either network servo motor drive based on CAN bus or various sensors. Data of multi-path CAN bus can communicated with CAN bus controller at the same time.

The main problem of distributed control system is synchronization of nodes. Multi-CAN bus architecture adopted in this work synchronize the data from all upper computer nodes (CAN bus controller of FPGA). This way, it satisfies broadcasting frame synchronization standards of CAN Servo communication protocol. Thereby CAN Servo communication protocol extending to multi-CAN bus is realized, and CAN bus servo control and synchronization are achieved.

Embedded system platform is formed by ARM processor and Real-Time Application Interface (RTAI). In the cockroach robot control system, the ARM processor adequately performs robot's tactile and visual signal processing, path planning, motion control, etc. RTAI, a real-time extension of Linux, allows a user to write applications with strict timing constraints for Linux. It has easy transplant characteristics, and is well suited for embedded applications. The software system based on ARM and RTAI is divided into non-real time tasks and real-time tasks.

Non-real time tasks are not related to controls running in Linux. They include human computer interaction, upper network communication, system tactile signal and visual signal acquisition, etc. Real-time tasks run in RTAI, such as path planning, motion control and interpolation process, and servo control requiring low-level sensing and position servo information processing. External interrupts utilize hardware interrupts of RTAI to further enhance real-time servo control, which allows for processing of system emergency and changing servo signals in real time. Real-time tasks implemented in RTAI communicate with Linux tasks through RT FIFO provided by RTAI.

The adoption of the embedded distributed network control system has the advantages of both network servo control and centralized control. Its bus controller is based on FPGA, and the topology form adopts star topology and bus topology. Embedded distributed control system based on ARM and FPGA provides information processing at stages and accurate servo control.

5.2 Real-time information processing and transmission

Multi-sensor information fusion based on FPGA technology is adopted to carry out pre-processing and encoding of sensor signals. Then the real time sensor information is transmitted to the robot master controller CAN data bus. The sensor information sources are primarily vision and tactile sensors. In such a complex system containing multi-sensor information, state space variables are inter-coupled owing to modelling error, external disturbance, load fluctuation, and imponderable dithering of cockroach robot's movement causing position error. Thus it is difficult to design and implement filter and controller in state space.

A possible approach being evaluated is to use Backstepping disperse adaptive controller based on robust information filter. The basic idea of this design method is to convert system state space variable to information space variables by robust information filter. System filter and controller can be designed by utilizing structure simplicity of expressing system information space variable. Returning to state space after solving information space, state variables can be solved through inverse transforms. This way, not only does it greatly simplify the design of filter and controller, but also provides a multi-sensor information fusion approach recovering more complete system information from local information.

The research on Backstepping disperse adaptive control scheme involves five steps progressively: i) lumped linear system, ii) disperse linear system, iii) disperse non-linear and model uncertain system, iv) adaptive control of disperse non-linear and model uncertain system by designing robust information filter, and v) K steps advance distributed evaluation arithmetic to effectively cover time delay and design Backstepping disperse adaptive control scheme based on robust information filter.

In developing sensor information processing system and control arithmetic based on SOPC technology, the information processing system is realized through integrating DSP module, RAM, ROM, CPU, etc. into a single FPGA. Data processing is carried out in both software and hardware. Internal hardware circuit employs multi heterogeneity array based on logic cell concept. It adopts building block design. Each module has its own storage and processor. Emulating biologic neural neurons, function modules (FM) are connected by time tag event module (TM). TM acts like the synapsis of human nervous system and is the handshake interface between function modules. External information from FM first enters TM, and TM determines the work mechanism and property of FM.

Each TM communicates with immediate function modules. Each FM's function can be described as different models, such as state oriented model, activity oriented model, structure oriented model and data oriented model, etc. Furthermore new models are formed by combining these models. The general structure of modular neural network system of FPGA is shown in Fig. 11.

It is important to simplify computation in FPGA design. Chip-level optimization is needed to implement control arithmetic to meet the stringent real-time operation requirements of the intelligent control system for cockroach robots

The internal board-level of information processing system bus adopts Xilinx RocketIO™ Multi-Gigabit Transceiver (MGT) - high speed data transmission technology, and accommodates different protocol designs of bandwidth from 622 Mb/s to 3.125 Gb/s per channel. Transceiver supports data rate as high as 3.125 Gb/s per passage and can satisfy various requirements of increasing data transmission rate. Output of information processing system adopts Low Voltage Differential Signal (LVDS) interface, and data output can reach 655Mb/s. Terminal adaptation has low power consumption, low radiation and fail-safe characteristic to ensure reliability.

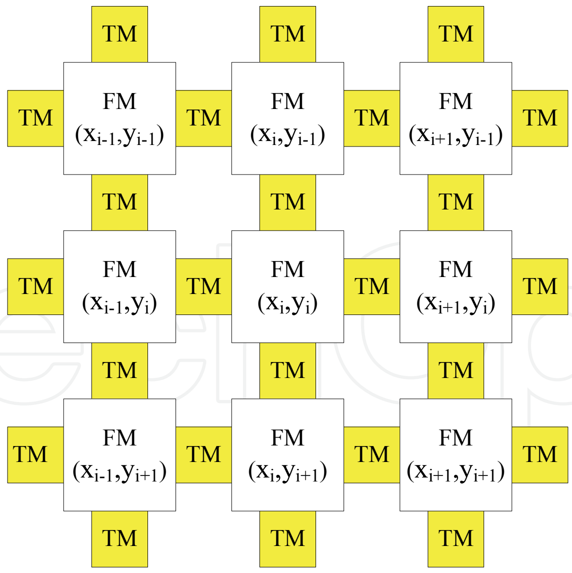

Fig. 11. Modular neural network system of FPGA

The internal information processing and control arithmetic adopts neural network technology, parallel processing of a large amount of information, and large-scale parallel calculation. The information system has plasticity and self-organization. It can realize system's study improvement mechanism when being triggered by external environment incentive conditions. Adaptive error compensation in information processing is achieved by changing internal programmable hardware structure parameters and software arithmetic. Information processing and information storage are combined, which differs from conventional computers whose storage address and content are separate.

5.3 FPGA-Based Motion Controller

Bionic cockroach robot requires high redundancy control. Besides controlling each walking leg efficiently and precisely, inter-harmony of six legs is another difficulty for control system. The control system has to deal with interferences among walking legs, and to complete corresponding movements exactly. Furthermore, bionic function demands that cockroach robot must adopt different movement modes based on different circumstances, which pose further challenges to control system design.

Because of very complex movement and smooth motion control in a highly dynamical environment, conventional dynamics control methods are found to be unsuitable for the movement control for two reasons:

Modelling error, external disturbance, load fluctuation and temporary set of limb may cause position errors.

Processing of a large amount of sensor information may lead to time lag.

For these reasons, backstepping disperse adaptive control method has been proposed for real-time movement control in the presence of position errors and time lag of sensing information. Equally important is to design a method that can execute real-time motion control at high speed.

With the rapid development of the semiconductor industry, SOPC technology has attracted more and more attentions. It is a new comprehensive electronic design methodology requiring skill sets of EDA software, hardware description language, FPGA, computer components and interfaces, assembly language or C language, DSP algorithms, digital communications, embedded systems development, construction, testing on chip system, etc. Comparing with the traditional design technology that has difficulties in meeting the needs of system, network, multimedia, high speed, low power consumption, and other applications, SOPC can integrate functional module such as processor, memory, peripherals and multi-level user interface circuits into one chip. It has been increasingly favoured because of its flexible, efficient and reusable design features.

Cockroach robot is an intelligent system integrating bionics, mechanics, sensing, information processing, and intelligent control. In an attempt to equip a bionic cockroach with intelligence in a small volume, a new chip called "smart brain chip" based on FPGA and SOPC technology has been conceptualized for the prototype cockroach robot. Smart brain chip integrates DSP, memory, and external I/Os. It has the function of motion controller that includes PWM signal to control the speed and position of motor, RS485 communications, wireless network, and sensor data acquisition.

As illustrated in Fig. 12, the motion controller based on FPGA consists of modules such as data instruction interface module, axis management module, digital PID module, T-curve generation module, S curve generation module, data acquisition and processing module, PWM module, synchronized module, and interrupt management module.

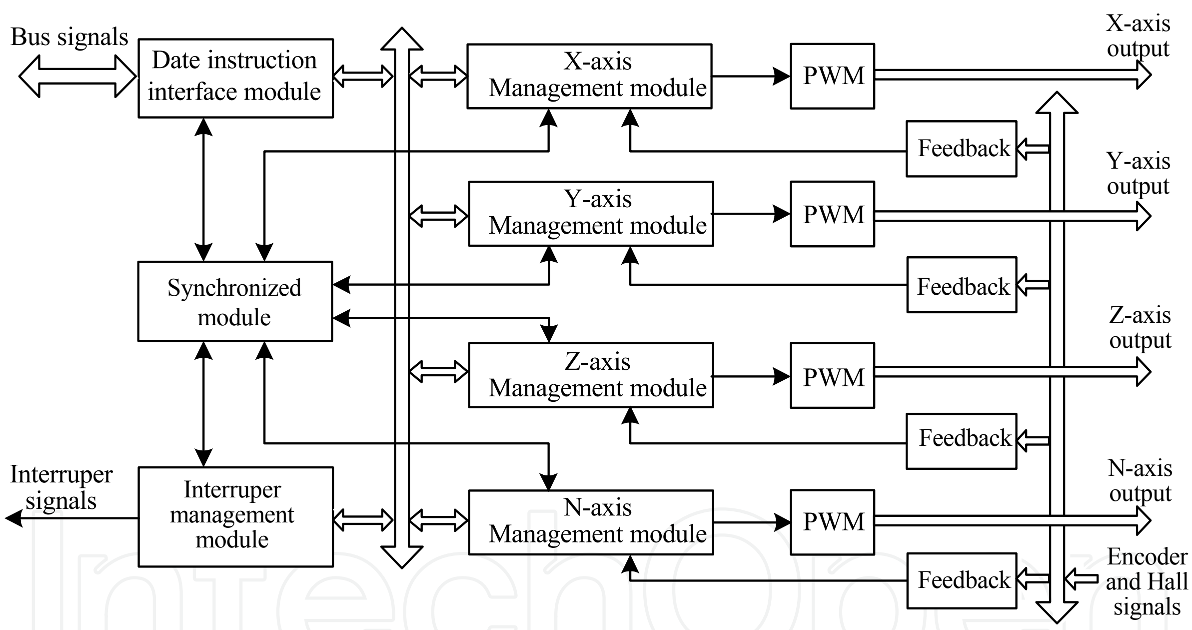

Fig. 12. The internal structure of motion controller

Low-level control algorithm is implemented as digital PID. The basic functions of the controller include data cache, control algorithms, signal feedback, and PWM generation. The controller is designed to control 18 DC servos motors in the robot joints.

6. Conclusions

The bionic cockroach robots have gone through a few generations over the past decades. However their motion versatility and sensing and navigation abilities are still far from their biological counterparts.

One key aspect of bionic cockroach robots is multi-domain fusion approach towards bionic mechanism design and motion smoothness control. It combines bionics, novel mechanism and disperse adaptive control theory to realize harmonious bionic motion. Parallel kinematic mechanism coupled with spring mechanism offers a realisable approach to emulate the functions of cockroach legs

For a robot to mimic the powerful sensing and navigation abilities of a cockroach, a multi-sensing fusion system has been proposed. It consists of binocular vision system based on infrared imaging, and tactical sensors using fibre optic sensors and position sensitive detectors.

The large amount of sensing information and real time motion control of 6-leg robots require careful consideration of control system architecture. This paper has conceptualised a distributed multi-CAN bus-mastering system based on Field Programmable Gate Array (FPGA) and Advanced RISC Machine (ARM) microprocessor. The system architecture provides stage treatment for control information and real-time servo control. It consists of there core modules: (i) nodes of CAN bus servo drive, (ii) distributed multi-CAN bus-mastering system based on FPGA, and (iii) software system based on ARM and Real-Time Application Interface (RTAI).

A new chip called "smart brain chip" based on FPGA and SOPC technology has been proposed to implement intelligent motion control for cockroach robot. It interfaces with devices including motors, encoders, hall sensors; and execute low-level control algorithm and smooth motion curve.

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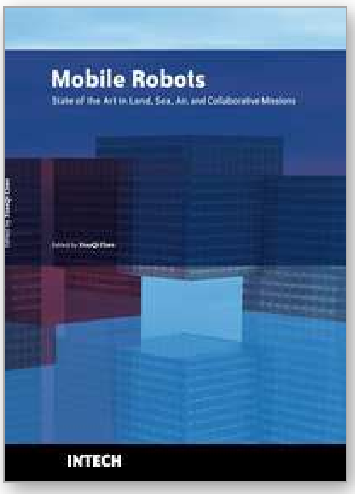

Mobile Robots - State of the Art in Land, Sea, Air, and Collaborative Missions

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Since the introduction of the first industrial robot Unimate in a General Motors automobile factory in New Jersey in 1961, robots have gained stronger and stronger foothold in the industry. In the meantime, robotics research has been expanding from fix based robots to mobile robots at a stunning pace. There have been significant milestones that are worth noting in recent decades. Examples are the octopus-like Tentacle Arm developed by Marvin Minsky in 1968, the Stanford Cart crossing a chair-filled room without human assistance in 1979, and most recently, humanoid robots developed by Honda. Despite rapid technological developments and extensive research efforts in mobility, perception, navigation and control, mobile robots still fare badly in comparison with human abilities. For example, in physical interactions with subjects and objects in an operational environment, a human being can easily relies on his/her intuitively force-based servoing to accomplish contact tasks, handling and processing materials and interacting with people safely and precisely. The intuitiveness, learning ability and contextual knowledge, which are natural part of human instincts, are hard to come by for robots. The above observations simply highlight the monumental works and challenges ahead when researchers aspire to turn mobile robots to greater benefits to humankinds. This book is by no means to address all the issues associated mobile robots, but reports current states of some challenging research projects in mobile robotics ranging from land, humanoid, underwater, aerial robots, to rehabilitation.

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