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Force Sensors in Hexapod Locomotion[*]

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1. Preface and Introduction

1.1 Preface[†]

The field of biorobotics has developed and flourished as a multidisciplinary interface between biologists and engineers (Ritzmann et al., 2000; Webb & Consi, 2001; Ayers et al., 2002). Collaborative work in the field initially arose from the recognition that studies of animal locomotion could provide insights in solving complex problems in the design and control of mobile machines (Beer et al., 1998). For example, some animals are remarkably successful at efficiently traversing irregular and non-horizontal terrains with great agility. Understanding the principles of leg and foot structure and the neural mechanisms of control of limb movements provides insights that can be emulated in the construction and regulation of legged robots to similar advantage. These insights have been successfully applied both to legged machines that resemble animals in their design and to robots that incorporate these principles more abstractly (Quinn et al., 2003).

These interactions have also been mutually beneficial in providing biologists with new methods to analyze living systems (Ritzmann et al., 2000; Webb & Consi, 2001). Computer simulations of walking have been completed for a variety of animals (cats, insects, humans) using control systems that reproduce elements of biological sense organs, muscles and neural pattern generators (Dürr et al., 2004; Ekeberg et al., 2004). In some studies, robots and computer control systems have been directly interfaced with animal nervous systems to analyze the properties of neural networks (Szücs et al., 2000).

The engineering method of Finite Element Analysis has also emerged as an important tool in analyzing biological structures. It has been applied to problems as diverse as understanding the biomechanics of extinct animal species (Alexander, 2006) and the effective design of artificial joints in humans (Ramos et al., 2006). It has also been utilized in neuroscience in analysis of biological sense organs to understand their mechanisms of transduction of mechanical forces (Hossl et al., 2006). This chapter describes studies we have

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performed using Finite Element Analysis to model the information provided by sense organs during locomotion. These studies have provided insights that could not be obtained using methods of contemporary neurophysiology due to technical limitations. In addition, they represent an approach that combines data from neurophysiological and behavioral studies with results from the application of engineering methods to provide insights in the encoding of forces that can be used in the design of legged vehicles.

1.2 Introduction

The control of forces that occur during locomotion is a problem that is common to animals and legged robots. In both systems, it is necessary to regulate forces to actively support weight, produce propulsion and counter unexpected perturbations due to loss of friction with the substrate. Force regulation becomes a formidable problem when traversing irregular or non-horizontal terrains. Adjustments to changes in the orientation of the gravitational vector must be integrated with mechanisms controlling body height and leg position. In a terrain with unknown geometric and material properties, a force control strategy is more appropriate than a position control strategy. Impedance control of each leg and utilization of positive load feedback (Prochazka, 1996) tremendously increase the performance of walking and climbing. Some animals, including insects, are able to make these adjustments based upon information provided by sense organs in the legs, without separate mechanisms (e.g. gyroscopes or inclinometers) to detect their orientation in the gravitational field. In recent years, biologists have increasingly appreciated that force or load sensing plays a vital role in insect locomotion (Duysens et al., 2000; Delcomyn et al., 1996). During locomotion, insects invariably sense not only the positions of their joints but they also indirectly measure the load in each of their legs via strain sensors, as they walk, climb, and negotiate obstacles. They also adjust muscle tensions and joint compliance as they change speed or load conditions (Bässler & Büschges, 1998).

In general, load sensors fulfil four major functions in animal systems (Prochazka, 1996). These sense organs can:

a) Detect the level of force and its rate of change during locomotion – Sense organs that detect forces in animals are activated by mechanical deformation (Zill, 1990). In the legs, these receptors are found in muscle tendons or are embedded in the exoskeleton (in invertebrates). The coupling of the sensors to these structures limits their responses and allows them to specifically detect the magnitude and rate of change of forces acting upon the legs.

b) Provide information about force direction during stance – Most force detecting sensors in biological systems are directionally sensitive (Zill, 1990). The maximal responses occur when forces or strains are in a specific orientation (along the muscle tendon or in a particular direction of compression of the exoskeleton). In walking, these forces are largest during stance, when the load of the body is placed upon the legs and forces are generated to support, propel and stabilize the animal.

c) Detect sudden force decreases (as in slipping or instability) – Most biological sensors produce continuous signals (trains of action potentials) that reflect the magnitude of forces applied to the leg. Decreases in these signals can therefore be used as indicators of loss of friction or leg slipping.

d) Enhance muscle activity through feedback during support or propulsion – The signals from biological sensors are processed in the central nervous system (Bässler

& Büschges, 1998). Many force sensors can elicit reflexes that produce rapid activation of leg muscles through these connections.

The studies described in this paper provide insights into mechanisms by which load sensors in insect legs can contribute to each of these functions. A better understanding of these mechanisms may lead to improvements in their applications in legged robots and potentially enhance the locomotory capabilities of these vehicles.

This paper describes how finite element analysis (FEA) was used to develop detailed structural models of cockroach trochanters, a small segment connecting the coxa and femur that incorporates four groups of strain receptors. FEA models of front and rear legs incorporating these trochanters were loaded with representative foot forces predicted from dynamic simulations of modelled cockroaches walking and climbing. Strains at the receptor locations were measured and compared for different loading conditions and conclusions were made regarding how it is possible for the cockroach to decode these data, determine its detailed loading condition, and use it to perform the four functions described above.

2. Insect strain sensors

Insects possess biological strain sensors, called campaniform sensilla, on their exoskeleton (Zill, 1990). These receptors have been extensively studied as a model system for understanding force detection. These sense organs are similar to strain gages and encode forces through compressive strains that are generated in the insect exoskeleton. A campaniform sensillum (Figure 1) consists of a sensory neuron located in the epidermis. The nerve cell has a dendrite that passes through a canal in the cuticle and attaches to a thin cuticular cap at the surface of the exoskeleton. The design effectively functions as a local stress concentrator that distorts the cap when strains are transmitted through the cuticle. The cap, however, is asymmetrical and several studies have shown that campaniform sensilla respond best to forces that act perpendicular to the cap's long axis. There are eleven groups of campaniform sensilla on the cockroach leg. Four groups are found on a small segment (the trochanter) and form the largest aggregation of receptors in the leg (Zill et al., 1999). The cuticular caps of each trochanteral group have a specific orientation with all individual receptors within a group arranged approximately in parallel.
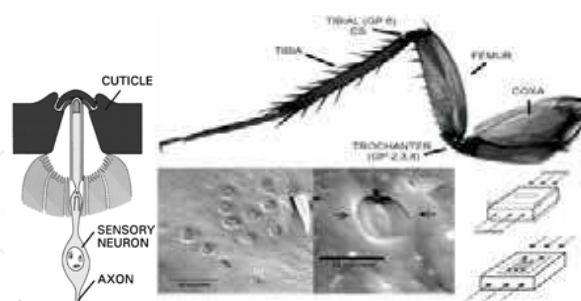

Fig. 1. Structure and locations of strain receptor groups in a cockroach leg; Each receptor consists of a sensory neuron whose process attaches to a cap embedded in the cuticle. The caps are oval shaped and organized in groups (as seen in the scanning electron micrographs in the center). Each receptor functions like a strain gauge and is excited by compressive strains in the exoskeleton that act perpendicular to the cap long axis (small arrows). Most strain receptors are found on the trochanter, a small segment in the leg (photograph of cockroach hindleg).
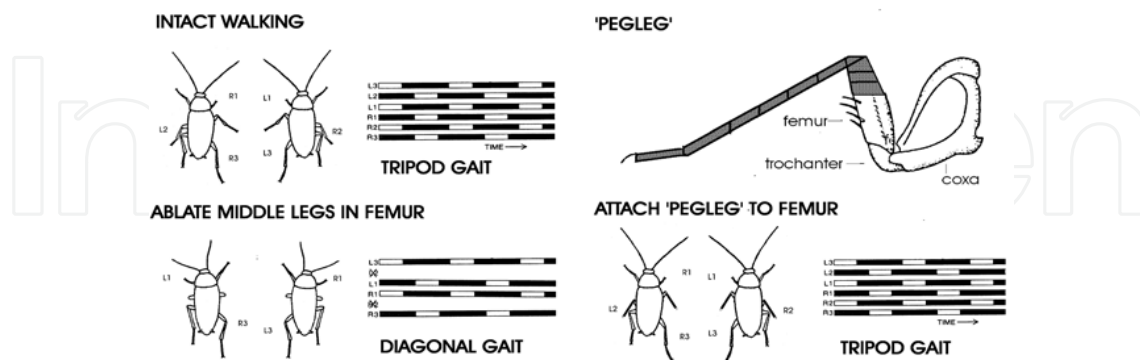
Figure 2: Peg leg experiments demonstrate the importance of sense organs of the trochanter in walking. The diagrams show the patterns of leg lifting in swing (dark bars) and placement in support during stance (light bars) as well as drawings of the legs in stance. Intact animals often walk in a pattern in which legs are lifted in groups of three, leaving a tripod of support. After ablation of the middle legs (leaving small stumps) the pattern of movement shifts to a diagonal gait, in which front and hindlegs of one side alternate. Small "pegleg" extensions were attached to the stumps, which still had intact trochanteral segments. Animals were able to use the prostheses in support and gaits returned to the pattern seen in intact animals. These experiments support the idea that signals from the proximal leg are necessary and sufficient to allow for limb use in support.

A number of studies have shown that the trochanteral groups can have decisive effects in the regulation of leg use (Wendler, G. 1966; Noah et al., 2004). The importance of the trochanteral campaniform sensilla in locomotion has been demonstrated by studies that have examined walking after partial leg ablation and addition of "pegleg" prostheses (Wendler, 1966). In intact animals, legs are often lifted in swing in pairs or groups that can produce "tripod" gaits. After ablation of the middle legs (leaving the trochanteral segments intact but unable to contact the substrate) the pattern of movement is altered and legs assumed a diagonal gait, similar to quadrupeds (Figure 2). However, addition of a prosthesis that permits contact and force development restores leg use. Noah et al. have extended these studies by recording from muscles in the "pegleg" and shown that normal patterns of activity occur if the leg can engage the substrate (Noah, 2004). However, when leg stumps were too short to reach the walking surface, abnormal multiple bursts occurred in single steps (Hughes, 1952; Delcomyn, 1985). These studies strongly suggest that signals from the trochanteral campaniform sensilla (and potentially other receptors of the proximal leg) are sufficient to allow for muscle activities to be sustained and for the leg to be used in support and propulsion in walking.

However, the activities of the trochanteral receptors have only been recorded in restrained or dissected preparations. Studies by a number of authors (Zill et al., 1999; Delcomyn, 1991) showed that the receptors could be strongly excited by forces applied to the leg when joint movements were resisted. Furthermore, these results suggested that the forces were encoded by different groups as an array rather than as sensors dedicated to particular force vectors. For example, two groups of sensilla (Groups 3 and 4) were shown to encode forces applied to the cockroach leg in the plane of joint movement of the adjacent coxo-trochanteral joint (Zill et al., 1999). The receptors within a group exhibited fixed patterns of

recruitment that could differentially indicate when force levels are adequate to provide support and propulsion during walking. Thus, these studies implied the sense organs could readily encode forces during locomotion. However, recordings of sensory activities could not be performed in freely moving animals due to technical constraints.

3. Modeling receptor excitation using finite element analysis

The anatomy and directional sensitivity of the receptors have provided the basis for modeling the responses of the trochanteral groups using Finite Element Analysis. The detailed structure of the exoskeleton was first reproduced by imaging the cuticle via confocal microscopy (Zill et al., 2000). This technique permits optical sectioning of solid materials as a series of digital images. The images were assembled and the cuticle was reconstructed in three dimensions using commercial software (Voxblast). Surface extraction algorithms were used to create files that mapped the inner and outer surfaces of the trochanteral segment. Those files were converted to a format compatible for stress analysis (Figure 3, meshed shell surfaces). These models preserved the values of thickness of the cuticle. It was also possible to precisely determine the locations and orientations of the individual groups of campaniform sensilla as nodes in the model. These FEA model trochanters were then incorporated into model "legs" of appropriate dimensions.

Forces were applied to the models at levels and orientations that occur during walking and climbing (Ramasubramanian et al., 1999; Kaliyamoorthy et al., 2001). Values for material properties of the cuticle were utilized from previously published studies. The strains at the specific locations and orientations of the cuticular caps were measured. Compressions that were greater than the threshold for receptor activation (as determined from physiological studies (Zill, 1999, *et. al*) were considered to produce excitation of the groups. These techniques have also been applied to forces that mimic the actions of the animal's leg muscles, which generate support and propulsion in posture and locomotion.
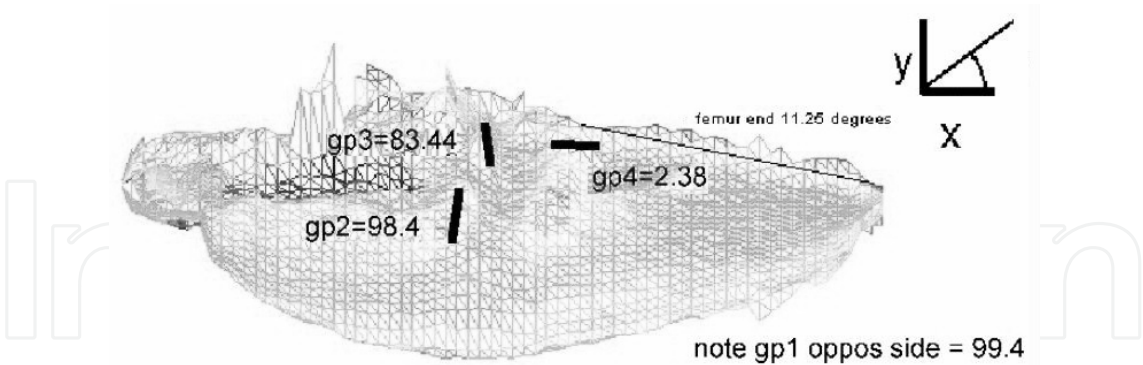

Fig. 3. Finite element model of the trochanter. A model of the trochanter of the cockroach front leg is shown. This model was derived from a three dimensional reconstruction of the exoskeleton obtained through confocal microscopy. The image shows the thickness of the exoskeleton as a grey scale code (thickest regions are dark, thinnest are light). Receptor groups are identified by their location and the numbers (and bars) indicate the angle of the orientations of the long axis of the caps of each group.

The error in the reduction of resolution of the data (polygon file) generated by the confocal microscopy software to a mesh compatible with FEA was estimated by a convergence method to be 3.25 percent (Flannigan, 1998). Also, there are local variations in the mechanical properties of cuticle surrounding the receptors (Chapman et al., 1973) that would tend to increase their sensitivity (cuticle is more compliant) so that calculations of responses probably represent underestimations. Lastly, while the force levels used in the model during walking and climbing are derived from simulations based upon inverse dynamics (calculated with assumptions, e.g. frictionless joints, rigid segment structure), these forces are in general agreement with data on ground reaction forces experimentally measured during cockroach walking (Full et al., 1991).

4. FEA of receptor responses during walking and climbing

A series of FEA experiments was conducted on the models of the trochanters of both the front and rear legs of cockroaches. Forces were applied to the models using data from dynamic simulations of cockroach walking (Nelson, 1995) and climbing (Choi, 2000) and the results were analysed to model the patterns of activation of the receptors.

4.1 Walking Studies

The results of the studies from simulations of walking for the front and hind legs are shown in Figures 4 and 5, respectively. The front and hind legs of cockroaches are similar in structure but differ in their size and use (Full et al., 1991; Kram & Full, 1997). Both legs have the same (homologous) groups of campaniform sensilla on the trochanter. However, they show different patterns of strain that would lead to excitation of the receptors during walking. In the front leg, analysis of strains using FEA (Figure 4) showed compressive strains (at levels that would result in activation) at the locations of specific groups of receptors (Group 4 and Group 1). The strains measured at these groups were high during both mid stance and late stance. Measurements at the locations of other groups showed only tensions that would not produce activity in the sensors. Thus, the different groups of sensors on the trochanter showed differential sensitivities to forces that occurred during walking.

A different pattern of activation was found in the rear leg (Figure 5). Compressive strains (at the orientation to produce sensor responses) were found predominantly in a single group (Group 3). Group 3 strains were high during the early phases of stance while showing reduced activation during late stance. In addition, much lower levels of excitatory strains were seen in Group 1. Group 4, which was strongly activated in the front leg, showed no periods of compression in the rear leg. These differences may be related to the orientations and uses of the front and hind legs that result in different forces. The plane of movement of the intrinsic leg joints is more vertically oriented in the front leg than in the hind leg. This orientation is suitable for the front leg to generate forces in the vertical plane (F_z) and to potentially provide support through a large part of the stance phase despite its relatively small size. In contrast, the rear leg is almost horizontal in orientation and is larger and more powerful. The rear leg generates much of the forward propulsive force in locomotion (F_x) (Full et al., 1991).
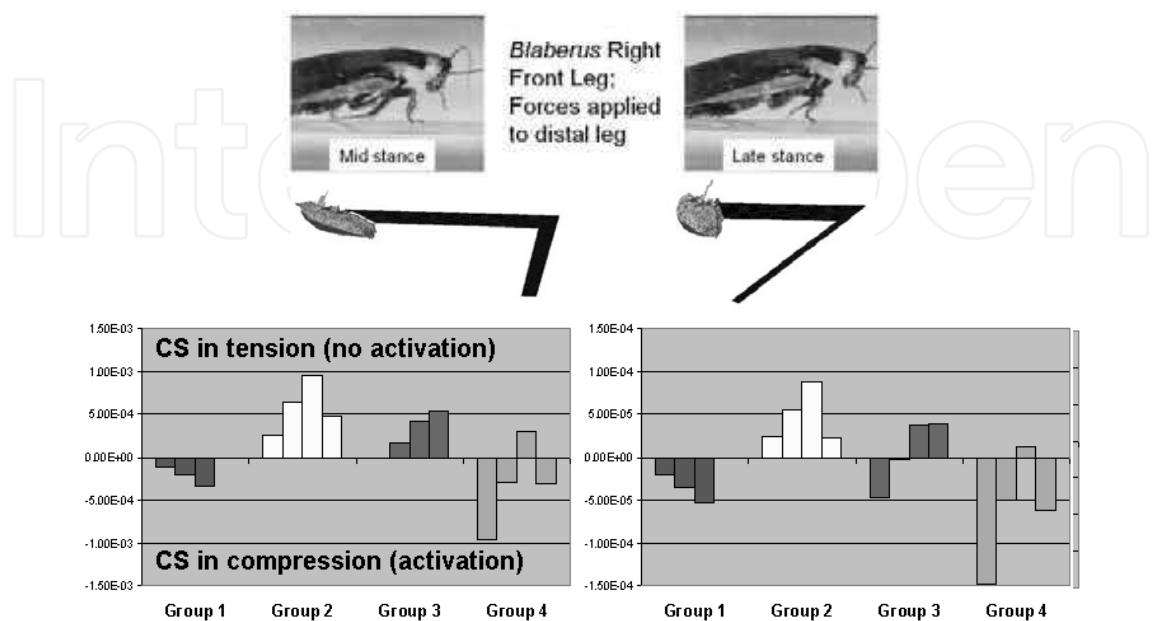
Fig. 4. Strains occurring in the cockroach front leg during walking – The model shown in Figure 3 was attached to structures that were of similar size and proportion to the other segments of the leg. Forces were applied to the distal end of the "leg" at levels and orientations determined from a simulation of cockroach walking. The lower graphs show the strains at the locations of the groups of trochanteral sensors (Groups 1–4) during mid and late stance. Compressions perpendicular to the cap long axis are negative and would produce activation of the sensors. Specific groups of sensors are activated during walking (see text for details).
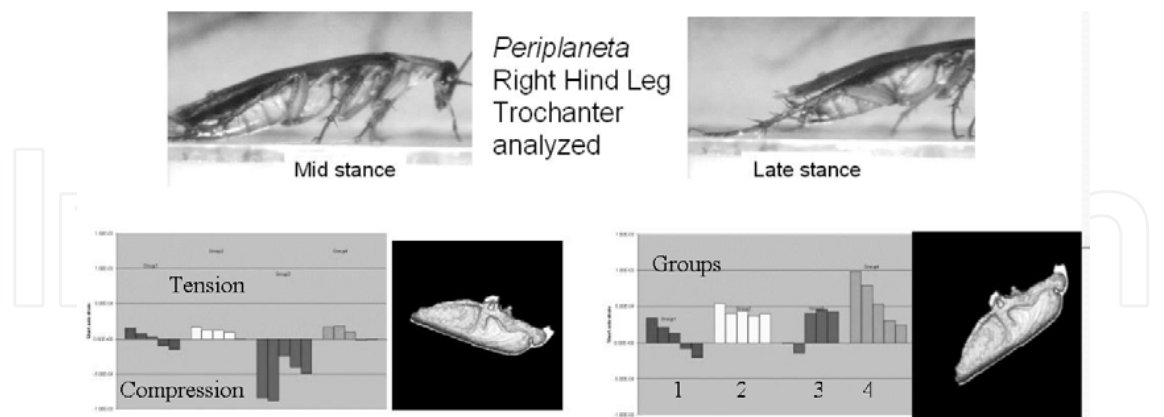

Fig. 5. Strains in the cockroach hind leg during walking (similar to Figure 4) – A model was also constructed from confocal images of the cockroach hindleg trochanter. Different groups of sensors show strain excitation in the hindleg than are activated in the front leg. Activation is maximal in mid stance, when the leg provides greatest support of body weight.

4.2 Climbing Studies

Studies of the patterns of strains occurring in the front and hind legs during climbing have provided insights into how the array of sensors can encode specific force vectors during adaptive locomotion. The front legs of the cockroach are the first to interact with obstacles during a climb (Watson et al., 2002). Some of the receptor groups in the front leg (for example Group 3), which did not show activation during walking, were excited during specific phases of climbing (Figure 6). These receptor groups could be activated by the additional forces needed to surmount an obstacle. This differential excitation prompted the question whether the receptors encode specific vectorial forces during walking and climbing. Figure 7 is a plot of the strains occurring at nodes of Groups 2 and 3 in the front leg trochanter vs. the magnitude of forces that are exerted in propulsion (F_x). There is a strong correlation in that both Groups 2 and 3 show excitation when the forces are positive (accelerating the animal forward) and are inhibited when the force direction is reversed (braking forward movement). Thus, the specific activation of the groups of trochanteral sensilla may be related to the particular forces occurring during climbing: the front legs which normally predominantly decelerate forward motion in walking may act to propel the animal over the obstacle during climbing. Other studies, in which individual force vectors were doubled or reduced to zero, also indicate correlation between receptor excitation and preferred direction of vectorial forces. Thus, the system may be able to detect the magnitude of specific force vectors based upon the preferential sensitivities of individual groups to particular force directions.
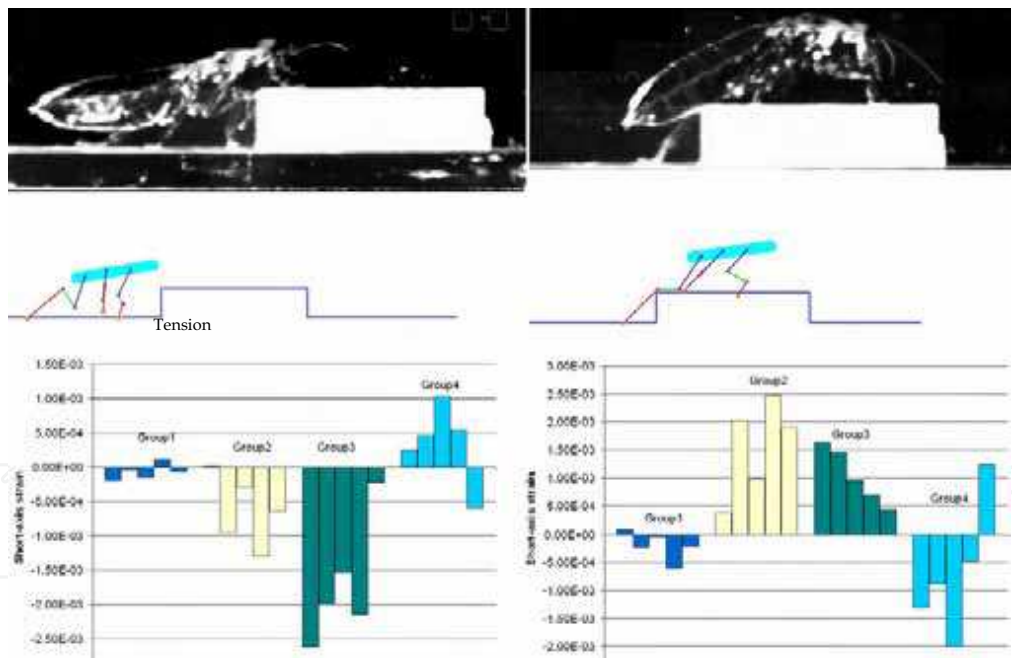

Fig. 6. Patterns of strain and group excitations occurring in the front leg during climbing – Forces were applied to the model at levels and orientations derived from a simulation of a cockroach ascending a small block. Different groups of sensors showed compressive strains during climbing, than had been found during walking. The pattern of excitation of groups was specific to the phase of climbing.
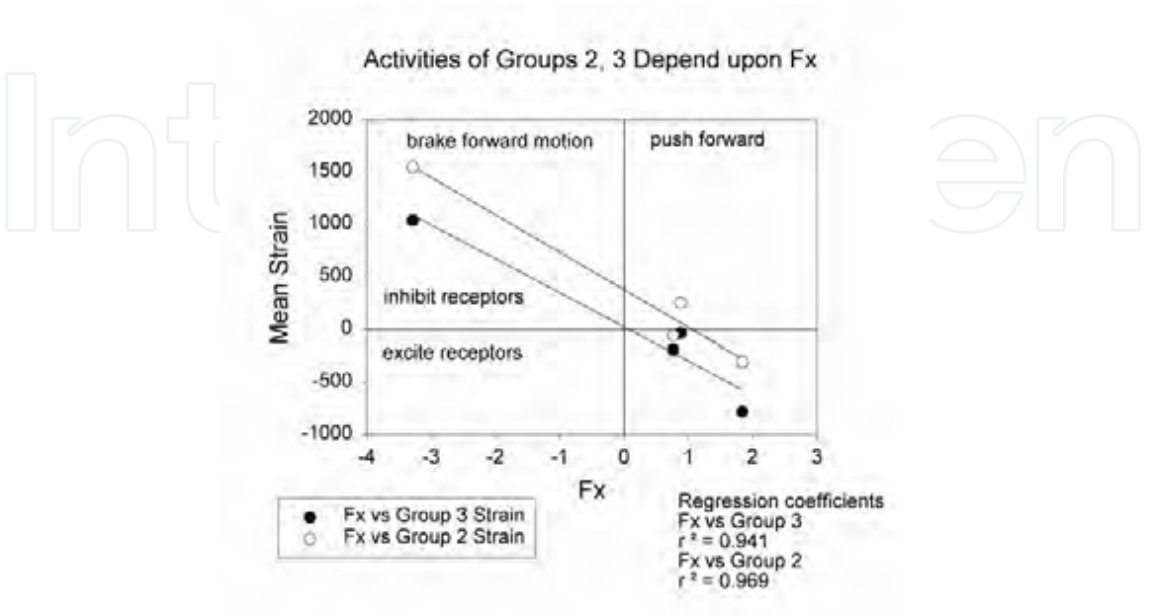
Fig. 7. The amplitude of strains is correlated with the magnitude of specific force vectors – Plot of the mean strain occurring in Groups 2 and 3 vs. amplitude of forces acting in propulsion. Excitation of the sensors during climbing is strongly correlated with forces that push the animals forward; the receptors are inhibited when forces act to brake forward motion.

5. Summary of findings

The results presented above support the idea that receptors on the exoskeleton can serve as specific load indicators during walking and climbing. Table I is a qualitative summary of the activation patterns of the groups of trochanteral sensors on the front and hind legs, as determined in the present tests and in a number of previous studies (Ramasubramanian et al., 1999; Kaliyamoorthy et al., 2001). Individual groups are scored as being strongly (indicated by X) or weakly (x) activated according to the magnitude of the compressive strains that were measured at the locations in the FEA model. "(-x)" denotes mixed response of sensors (some receptors activated within a group, others inhibited). The "pegleg" tests were performed by applying forces to the leg in the femoral segment (adjacent to the trochanter, see Figure 1) similar to the situation occurring in the classic "pegleg" experiments. Forces were applied to the model in directions that would produce flexion or extension of the coxo-trochanteral joint. The lower half of the figure summarizes results obtained in studies using simulations of walking and climbing. In addition, in the pegleg and walking studies, we also tested responses to forces applied at the points of attachment of leg muscles. Other tests were performed in which forces in individual directions were doubled, to test the response of sensors to specific force vectors in the body reference frame.

These studies support the idea that load sensors (campaniform sensilla) can fulfil the following functions:

a) <u>Detect the level of force and its rate of change during locomotion:</u> The FEA tests produced compressive strains at the locations of most groups of campaniform sensilla, indicating that the sensors can readily encode forces that result from the effects of body weight and inertia. These results are consistent with the biological literature on campaniform sensilla. Zill and colleagues (Zill & Moran, 1981; Ridgel et al., 2000) have recorded the activities of the tibial campaniform sensilla in the cockroach hindleg. They found that one subgroup, the proximal tibial sensilla, showed a discharge during walking similar to that found by FEA analysis in the present study. The proximal sensilla fired after the onset of leg contact and the discharge declined later in the stance phase. These receptors have also been shown to be highly sensitive to the rate of force application (Ridgel et al., 2000). Similar patterns of activity have also been recorded from sense organs that monitor strains in the exoskeleton in crabs: funnel canal organs of the dactyl show discharges that also reach maximum rates immediately following leg contact and continue at lower firing rates later in stance (Akay et al., 2001). Thus, the physiological data from a number of invertebrates suggest that the receptors that encode forces are active during walking and that activities are maximal during the stance phase.

b) <u>Provide information about force direction during stance:</u> Both the FEA tests in which forces were applied to the femur (pegleg tests) and the results obtained from simulations show that forces are encoded by the sensors as an array. It is important to note that sense organs in biological systems show adaptation to sustained levels of force and hysteresis to force decrements (Ridgel et al., 2000). If individual groups were dedicated to specific force vectors and only single measurements were made, difficulties might arise in accurately detecting dynamic increases and decreases in force levels. One advantage that the array of sensors may offer is that it could allow for finer discrimination by making multiple measurements of the changes in forces with sense organs of different sensitivities and thus, different degrees of adaptation and hysteresis. However, individual groups show preferential sensitivities to particular directions (F_x, F_z) that could be utilized to organize compensatory responses to sudden changes in load. Furthermore, the responses of groups in the front and hind legs reflect the similarities and differences in the forces they generate and undergo in locomotion. Both legs support the body weight during walking and climbing. Group 1 in the front and rear legs shows a high sensitivity to F_z (the gravitational vector). Information from this group could be used to assure that the support of body load is maintained in locomotion over diverse terrains. Information from the Group 1 sensilla in different legs could also be used in coordinating leg movements. However, the front and rear legs differ significantly in their contribution to forward propulsion. This is reflected in the differences in sensitivities seen in the front and rear legs to the effects of contractions of leg muscles and to F_x. As shown in Table 1, strains produced by the extensor muscle or by doubling of forces in propulsion (F_x) produce strong excitation of group 3. The same stimuli produce only modest effects in groups in the front leg.

c) <u>Detect sudden force decreases (as in slipping or instability):</u> The Finite Element tests also indirectly support the conclusion that the receptors could readily function to detect leg slipping. The magnitudes of the strains that occurred at the locations of the sensilla were closely related to the amplitudes of the forces that were applied to the leg. Thus, the receptor discharges should decrease rapidly if

forces in the leg suddenly decline and cease if contact with the substrate is not maintained. The indication of decreasing forces may be important in detecting the onset of leg slipping to allow for adjustments of muscle activities or leg position (Ridgel et al., 2000). These functions could be fulfilled by strain or force sensors both in biological and potentially in robotic systems.

d) <u>Enhance muscle activity through feedback during support or propulsion:</u> Physiological studies have shown the trochanteral receptors in the cockroach can strongly excite a leg extensor muscle that is a principal generator of leg movement and force (the trochanteral extensor, Ds) (Duysens et al., 2000; Zill, 1990). Thus, these results suggest that the sensors can provide feedback that could be used to enhance and sustain the activities of muscles to support body load and generate propulsion (Akay et al., 2001; Schmitz, 1993). Receptors in the crab also have been shown to produce reflex effects in leg muscles (Libersat et al., 1987). These sense organs are postulated to adjust activities of leg muscles to load and to aid in the coordination of leg movements. Thus, the physiological data from a number of invertebrates suggest that the receptors that encode forces are active during walking and can rapidly activate leg muscles at specific times during the stance phase.

Many groups of receptors also showed compressive strains both from external loads and from muscles that are active in propulsion. This may offer the advantage of rapidly monitoring both changes in load and the effectiveness of muscle contractions in countering those loads. This type of encoding is also seen in receptors of limbs of vertebrates (Golgi tendon organs) (Prochazka, 1996).

Table 1. Qualitative summary of the FEA experiments.

		Front Leg				Hind Leg			
		Group 1	Group 2	Group 3	Group 4	Group 1	Group 2	Group 3	Group 4
Peg Leg	Force Flex		x	X	(x)		x	X	x
	Force Ext	X			X				x
	Extensor muscle	x	x					X	X
	Flexor muscle	x	x			X		X	
Simulate Walking	Walking Load	X			X	x		X	
	Walking Extensor Muscle			x		X		X	
Simulate Climbing	Climbing elevate		x	X				X	
	Climbing rise			(x)	X			X	
Force Double	Fx				(-x)			X	
	Fy			X				x	x
	Fz	X				x			

Table 1. This table qualitatively summarizes the patterns of activation of different groups of sensors on the front and hindlegs in a number of tests, including the simulations of walking and climbing. In pegleg tests, forces were applied to the leg with joint movement resisted. (X – Strong activation; x – Moderate; (x)/(-x) – Mixed response). See text for discussion.

6. Principles for application in animal modeling and robotics

We have identified four load sensing and control principles based on the findings of these FEA studies that have particular applications to modelling of animal locomotion and control of legged vehicles. These are:

1) <u>Positive Load Feedback</u> – In the hindleg, the data in Table 1 clearly demonstrated that Group 3 sensilla show high levels of strain both to loads imposed upon the leg that mimic resistance to extension and to contractions of the extensor muscle that is active in generating propulsion. These elements could readily provide positive feedback in a walking animal and function to enhance the magnitude of muscle contractions and increase stiffness after the onset of stance (Zill et al., 2004). Positive feedback has been used in generating and regulating leg movements in a number of recent simulations (Ekeberg et al., 2004) and controllers (Kindermann, 2002; Dürr et al., 2004) that are based upon insect walking, and have also been utilized in simulations of vertebrate locomotion. In kinematically based models, signals of joint angular velocity are used as feedback signals (Dürr et al., 2004). However, direct use of force feedback may be particularly advantageous when traversing non-horizontal terrains, such as in walking on slopes or climbing or in carrying large loads. Positive feedback loops have often been viewed as undesirable as they are prone to be unstable. In some systems, muscle properties (length-tension relationships) that inherently limit force outputs may serve to limit instabilities (Prochazka, 1996). Studies of FEA models of the trochanteral campaniform sensilla suggest that leg geometry may provide an inherent limitation to feedback from sensors in the exoskeleton, as the mechanical advantage of the extensor declines as the joint angle extends (Nelson, 2002). This could readily produce high levels of positive feedback at the start of stance, but limit force generation as stance progresses. A similar pulse increase in feedback has been tested in control of Robot III, a cockroach inspired robot (Nelson, 2002).

2) <u>Selective detection of force: support vs. propulsion</u> – Individual groups of sensilla in the array are preferentially sensitive to force vectors in particular directions. This finding implies that the sense organs could readily provide specific signals to differentiate between loads that result from body weight versus loading that occurs to increased resistance in propulsion (as in specific phases of climbing (Watson et al., 2002). This would allow for selective use of specific force feedback in support vs. in propulsion. Support of body load has been regulated by negative feedback based upon positional signals (Dürr et al., 2004), but recent experiments suggest that information about both force and kinematic variables are integrated in the animal in generating support of body weight in standing and walking (Noah, 2004) in insects; (Pratt, 1995) in vertebrates). The problem of integration of kinematic and force data has been an area of intense research both in neurobiology and robotics (Zill et al., 2004; Ekeberg et al., 2004).

    These findings also represent additions that could be incorporated into behavior based control models (Kindermann, 2002). The model of Cruse, for example, is largely based upon control of kinematic variables, with few direct effects of load (e.g. Rule 5, (Dürr et al., 2004)). The addition of sensors that directly detect forces to these control systems would allow rapid adjustments to variations in load without potentially disruptive changes in joint angles. These sensors could also allow for use of both kinematic and force variables in controlling leg movements, as is shown by biological systems (Zill et al., 2004; Duysens et al., 2000). For example, in

animals, the onset of swing movements in walking depends both upon the position reached in extension (posterior movement) and upon unloading of the leg. The addition of sensors that preferentially detect a decrease in body load upon the leg (as occurs in the Group 1 trochanteral campaniform sensilla) could allow for incorporation of information from both variables into the control system.

3) <u>Monitoring Forces Close to Body</u> – A key observation on the organization of cockroach force detectors that may be of interest in design applications to roboticists, is that *monitoring forces at the hip or knee permits flexible use of the foot*. In the design of force sensors, sense organs that were equivalent to a load cell placed at the end of the leg might seem optimal. However, the structure of the insect foot (tarsus) provides a number of surfaces that can interact with the substrate (Larsen et al., 1997). The claws can actively grasp it and the arolium (a large sticky pad) can be actively pushed onto a surface by muscle contraction (Gorb & Beutel, 2001). Furthermore, on some surfaces, insects only use the pulvilli, which are sticky pads similar to the arolium but that are found under the tarsal segments (1–5). These pads maximize the surface area of contact of the tarsus. These features imply that the flexibility of the system prevents there being a simple point at the foot at which force could accurately be detected in all behaviours. For machines to gain similar flexibility of contact with the substrate, it may also be advantageous to utilize force sensors located in a leg some distance from the point of substrate contact. It could also be noted that the location of the sensors in the trochanter also allows for minimal temporal delays in conduction to the nervous system. This arrangement minimizes the calculations needed when force vectors are determined in the body coordinate system, in contrast to sensors placed at the foot.

4) <u>Advantage in Redundancy: Increased Safety Factor</u> – One further characteristic in the organization of strain sensors in insects is that they occur in groups and provide multiple measurements of force parameters. Insects apparently utilize this redundancy of measurements to produce signals from a number of sensors when forces are high (range fractionation, (Zill et al., 1999)). This is in contrast to the approach widely used in robotics, which is to have single sensors of high sensitivity. That approach has the disadvantage of being subject to potential loss of measurements if sensor failure occurs and is also subject to noise in the system. The use of multiple measurements endows the insect system with a considerable safety factor and may decrease noise in the signals of force parameters.

7. Implementation in legged robots

The four principles described above can be used to enhance the locomotion performance of legged robots. In fact, force sensors have been incorporated into a number of legged robots. As an example, Robot II sensed load at each of its joints and its control system used this information to enable its legs to comply with irregular terrain. TUM and Robot II reacted to load sensed in their legs to perform an elevator reflex to swing their legs over obstacles (Weidemann & Pfeiffer,1995; Espenschied et al., 1996). The elevator reflex in these robots was triggered only during the swing (return) phase of the leg. Both of these robots used only position information to switch their legs to and from stance and swing. They could have benefited from using load sensing to make this switch as in the second principle described above. The switch from stance to swing should depend upon load to avoid suddenly swinging a leg that is supporting a significant portion of the body weight.

Robot III, a cockroach inspired robot, makes uses of the third principle listed above, in having load sensors close to the body. It has strain gauges (Fig. 8) at locations equivalent to those where strain sensors are found in the cockroach (Nelson & Quinn, 1999). Strain gauges were positioned on the proximal end of the leg segment corresponding to the femur (Fig, 8, trochanteral sensors), similar to the location of the trochanter and trochanteral campaniform sensilla in cockroaches. The gauges were also oriented to detect bending strains in the plane of joint movement, similar to the cockroach trochanteral Group 3 receptors. Other strain gauges were located on the proximal tibia, at location corresponding to the well studied tibial group of receptors (Ridgel et al., 2000). Stance forces applied on its feet causes bending strains at these locations from which three-dimensional foot force vectors can be determined.

Several problems were encountered when implementing strain gauges on Robot III, which are typical in load cell design, but largely avoided in the animal's design because of the fourth principle described above (redundancy in measurements). Foil gauges were chosen over semiconductor gauges to avoid temperature sensitivity. They were placed in bridges to eliminate strain from loading other than from bending. The strain signals are weak and require amplification. Further, the signals are noisy and have to be filtered. Another problem is that the gauges are easily damaged and the loss of one sensor is a catastrophic failure of the entire load cell. Finally, they must be carefully calibrated. The fourth principle above suggests a different strain sensor implementation that would alleviate some of these problems. Instead of using a few carefully placed and well calibrated sensors, many sensors could be mounted in distinct groups on the leg. Noisy signals from individual sensors could be tolerated because the summation of their signals would filter the noise. Furthermore, the system could function well even if a number of sensors were damaged. This implementation requires micro strain gauges be manufactured in quantity on a membrane so that they could be mounted on the robot's legs. Unfortunately, we are unaware of the existence of such sensors.

Although experiments continue with strain gauges used in designs that closely follow the campaniform sensilla, we also have demonstrated that a pressure transducer located down-line from a pneumatic actuator produces a sufficient signal to determine actuator force (Kingsley et al., 2003). We found that strain gauges properly placed on the mounting elements of the actuators can produce sufficient signals for force feedback. However, pressure transducers can provide smoother signals, do not require amplifiers, and do not exhibit cross talk; all disadvantages of strain gauges (Kingsley et al., 2003). Force feedback can be attained through pressure measurements from the actuators, which, given actuator length, can be used to determine actuator force. However, we plan to utilize information from these sensors in accordance with general principles delineated by the FEA studies.

Force signals have also been implemented in controller design to resolve problems in regulation of leg movements. These systems incorporate positive load feedback and differential sensitivity to force vectors demonstrated in the FEA analysis. Positive load feedback, the first principle described above, has been shown to provide rapid load compensation by augmenting both the actuator's passive damping and the control system's active stiffness (Nelson, 2002). The positive load feedback loop used in the controller of Robot III is depicted in Figure 9 (see (Nelson, 2002) for details).

Furthermore, some authors have argued that measurements of these outputs are needed for adaptive locomotion. There is more to walking than gait coordination. The original stick insect mechanisms and network reviewed by Cruse (Cruse, 1990) simply decides when to transition legs between stance and swing phases. Nelson (Nelson, 2002) writes that "The algorithm tells you nothing about what to do *during* those phases to stabilize body posture

and motion." Indeed, gait coordination is a small part of the controllers for Robot II and Robot III. We anticipate that further work on force control based on these FEA results will provide the information needed to elegantly control legs during their stance phases and to therefore robustly support and propel the body dynamically over obstacles.
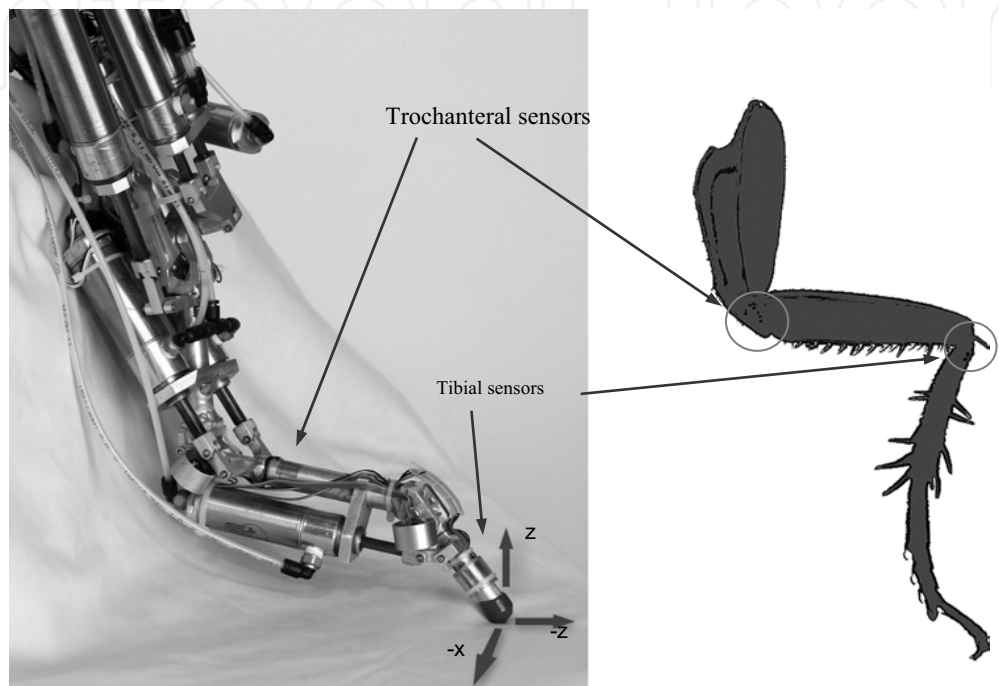

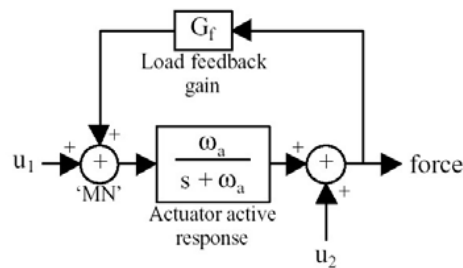Fig. 8. Equivalent load sensor locations on the right front leg of Robot III. Note that the foot has been removed from Robot III.

Fig. 9. Positive Feedback from Load Sensors.

8. Conclusions

Finite element analysis (FEA) was used to develop a detailed structural model of the cockroach trochanter, a small segment connecting the coxa and femur that incorporates four groups of strain receptors. The detailed structure of the exoskeleton was first reproduced by imaging the cuticle via confocal microscopy. The images were assembled and the cuticle

was reconstructed in three dimensions. Surface extraction algorithms were used to create files that mapped the inner and outer surfaces of the trochanteral segment, which were then converted to a format compatible for stress analysis. Nodes were identified in the FEA model at the locations of the strain receptors in the trochanter. FEA model trochanters for front and rear cockroach legs were then incorporated into simplified FEA model legs of appropriate dimensions so that they could be loaded with representative foot forces predicted from dynamic simulations of modelled cockroaches walking and climbing. Strains at the receptor locations were measured and compared for different loading conditions. The results presented in this paper (in light of previous work) indicate that the strain receptors in the exoskeleton can serve as specific load indicators during walking and climbing. Specifically, the load sensors (campaniform sensilla) can detect the level of force and its rate of change during locomotion, provide information about force direction during stance, detect slipping or instability, and enhance muscle activity through positive and/or negative feedback during support or propulsion. These functions are also desirable for load sensors for legged robots. Therefore, the load sensing mechanisms and associated control circuits found in animals can provide good models for implementation into legged robots.

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This book covers many aspects of the exciting research in mobile robotics. It deals with different aspects of the control problem, especially also under uncertainty and faults. Mechanical design issues are discussed along with new sensor and actuator concepts. Games like soccer are a good example which comprise many of the aforementioned challenges in a single comprehensive and in the same time entertaining framework. Thus, the book comprises contributions dealing with aspects of the Robotcup competition. The reader will get a feel how the problems cover virtually all engineering disciplines ranging from theoretical research to very application specific work. In addition interesting problems for physics and mathematics arises out of such research. We hope this book will be an inspiring source of knowledge and ideas, stimulating further research in this exciting field. The promises and possible benefits of such efforts are manifold, they range from new transportation systems, intelligent cars to flexible assistants in factories and construction sites, over service robot which assist and support us in daily live, all the way to the possibility for efficient help for impaired and advances in prosthetics.

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