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Multifunctional walking quadruped

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SUMMARY

A multifunctional 4 legged walking machine that is being developed in the Robotics Research Centre (NTU) is described. The major factors influencing the design requirements include minimisation of the weight of the machine and maximisation of workspace of the legs. The designed walking machine can adopt a variety of configurations, such as insect, mammalian, reptile or human. The device is invertable (i.e. can turn over). It can use its legs as manipulators, hence it can perform basic pick-and-place functions. A control system was built using the QNX real-time operating system platform. The software was designed using the client-server approach.

KEYWORDS: Omni-directional walking machine; Quadruped robot; Walking machine design.

1. INTRODUCTION

In the design of legged machines several important decisions, which influence the technical features of these systems, must be taken. As the most important problems we can list: the choice of mechanical structure and leg configuration (choice of number of legs, their kinematic structure, joint design), design of actuating and drive mechanisms (choice of motor types, evaluation of their power, design of motor location and assessment of methods of motion transmission from motors to the leg joints), evaluation of expected power consumption in relation to the machine's weight, payload, motion conditions (e.g. soft, hard terrain, inclined terrain, etc.) and assumed method of walk (speed of motion, number of legs supporting the body during walk, etc.). An important consideration is the adequate specification of the control system (on board/off-board control system, control software, hardware and software control systems architecture, distribution of the on-board utilities, cables, sensors which influences the stability conditions, etc.).

The machine's autonomy depends on the internal sensors delivering the information about the internal state of the device, and on the external sensors detecting the external environmental conditions. This information must be properly used by the control software which finally determines the machine's "intelligence".

2. RELATED WORKS ON THE MECHANICAL DESIGN

The mechanical efficiency of locomotion of the existing walking machines is low in comparison to that of living animals, and low in comparison with wheeled locomotion, but the expectation is that in the future artificial legged locomotion will be one of the most energetically effective sources of transportation.[1] The designer of a walking machine must consider the energy consumption which influences the choice of mechanical structure, the propulsion and power system. The optimisation of design for better energy efficiency has been studied for a long time. Mechanical locking of a leg in the support phase has been proposed.[2] According to our knowledge, in existing machines, a single motor is responsible for the actuation of an individual (or single) leg joint. Figure 1 illustrates the most representative leg design that can be found in existing multilegged prototypes. Figure 1a shows the basic insect leg configuration. This three link leg is generally used for average sized walking machines (e.g. 20 kg weight, 0.6 m body length, 0.5 m body width[3] which require a large support base. In this design motors are located directly in the joints, or the rotation of their shaft rotation is transferred through links, as it is the case of knee motion of the LAURON hexapod. In Figure 1b we can see the pantograph utilised in the leg design. The points A & B move linearly (usually driven by lead screw motors) and, if the mechanical linkage is designed carefully, point F can be made to closely follow a straight line. Such a solution was used in Japanese quadrupeds PV and TITAN,[4] in a big, heavy hexapod – ASV,[5] or in Finish MECANT.[6] Figure lc shows a 3-DOF leg design which employs a four bar mechanism (i.e. MEL-WALK,[7] KAISER[8]). Rotation around A produces the swing of point C. The rotary motion of A is obtained either by the rotary motor located at A, or by the change of link length BC, as it was done in MELWALK MARK II.[7] Figures 1d, e illustrate the one link leg. Two servo motors are attached back to back. Each motor is responsible for either the lift or swing axes. This solution allows the machine to be invertable (IOAN[9]). This kind of leg structure with servo-motors and a 2 degrees of freedom leg is commonly used in a variety of light, small legged vehicles (IOAN – Figure 1d, HERMES[10] – Figure 1e and others). Figure 1f shows a 3-DOF three bars leg design which employs two linear actuators for the leg lift and leg side motions and a rotary actuator for the leg swing action (i.e. AMBLER[11]). For

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comparison Figure 1g shows the design scheme of the LAVA quadruped with a two link leg and 3 revolute joints.

3. LAVA DESIGN

3.1. Mechanical design

To minimise the weight and increase the energy output each leg with its 3-DOF is driven through an inverse differential gear drive. Two motors are located in the hip section and the third is in the knee section (Figure 2). The hip motors work collectively to generate combined leg swing and lift. Motors are coupled through a worm gear system to ensure a stable system lock to allow the motors to power down when the legged vehicle merely needs to stand, thus saving electrical power. We used worm gears coupling for a stable system lock, but our goal was not only good mechanical efficiency but also a large leg work-space, which offers the ability to walk with many different gaits, and with different leg postures. Moreover, LAVA has an active over-turn ability. Similar capability is exhibited by the hexapod IOAN.[9] It can tip-over by the active motion of body segments. The "flexibility" in the adjustment of the leg posture offers the possibility of choice of posture in such a way that the relation between horizontal and vertical force components exerted by the leg on the ground can be chosen according to the expected ground friction coefficient (method of reaction forces calculation[12] and leg posture adjustment[13]).

Each individual leg section was carefully designed to provide individual lift and swing angles beyond 180 degrees, thus providing the vehicle with a high degree of motion dexterity to assume a variety of configurations beyond the basic walking and support functions (Figure 1g, Figure 2). Special care was taken to ensure that minimal obstruction was encountered between the legs and the body

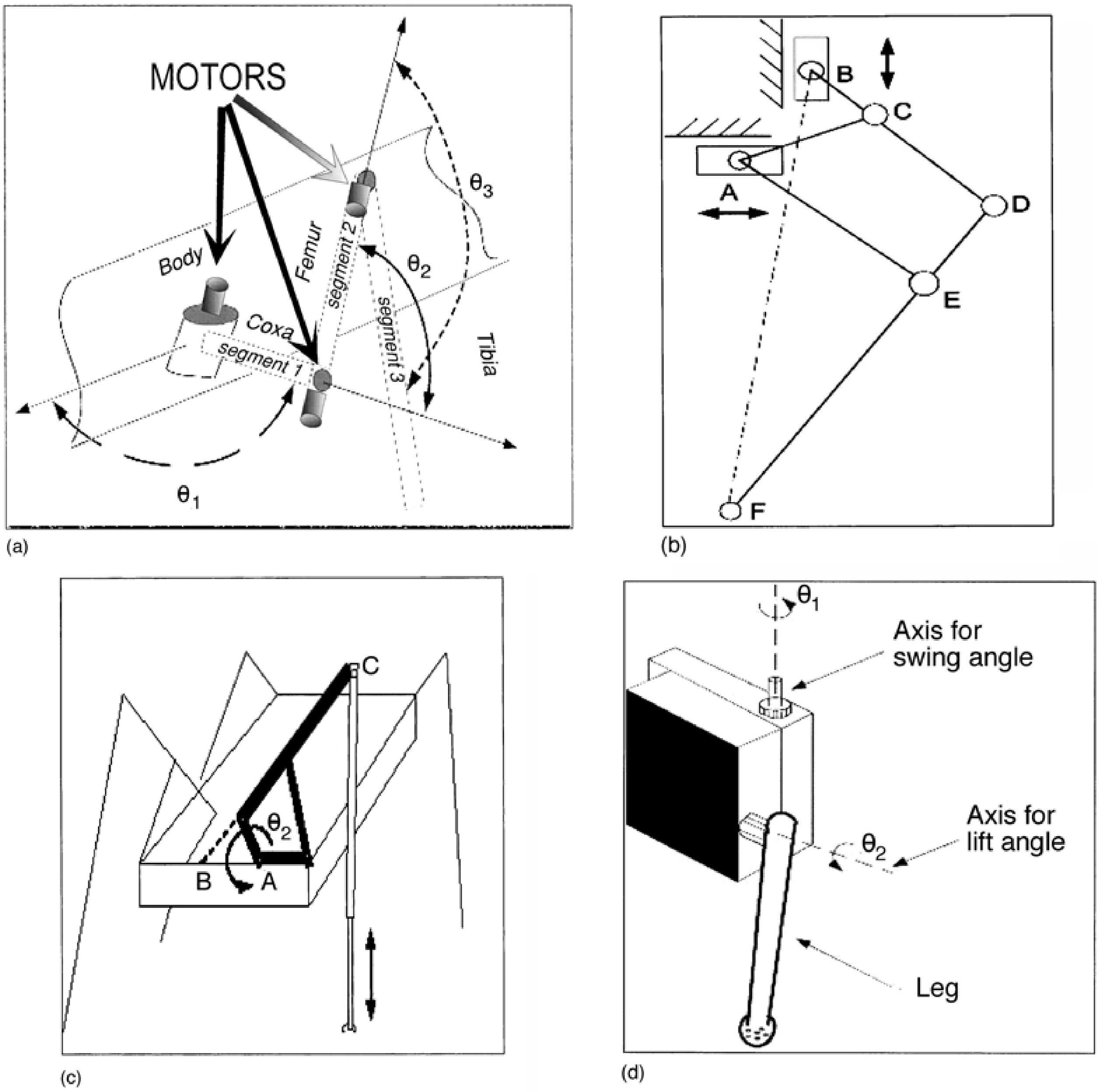

Fig. 1. Different ideas of leg design.

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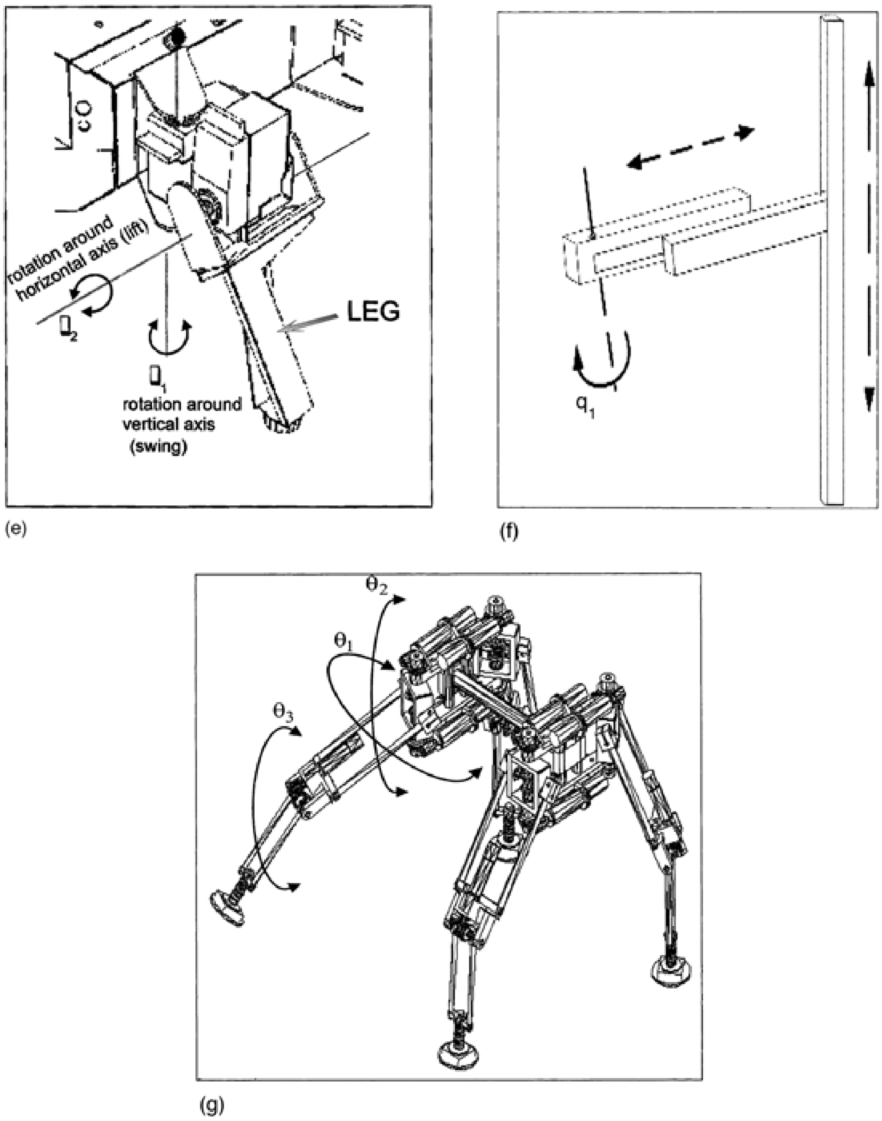

Fig. 1. Continued.

(Figure 3) when the legs were being driven through their large leg lift and sweep angles.

Such a design allows us to treat each leg as a single module and easily build machines with different number of legs. In our preliminary research we had a prototype with 2 wheels and 2 legs, next we build the LAVA quadruped; and finally we applied our design to the family of heavy hexapods (GROVEN I,II,III,IV).

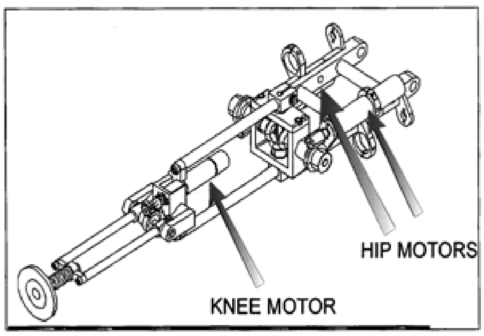

Fig. 2. Close up drawing of a single LAVA leg with a differential drive.

Each of the LAVA thigh motors (MAXON motors) is rated at 4.5W coupled through a 2 stage 19:1 planetary gear box and a 40:1 worm gear. The knee motor is rated at 3W with a 3 stage 76:1 planetary gearbox and a 40:1 worm gear. All motors are coupled to a 16 counts per turn 2 phase TTL compatible magnet digital encoder. At an average motor speed of 3850rpm, the thigh swing and lift speeds attain 30deg/sec, while producing a combined torque (both motors working collectively) up to 4Nm applied to the load. This value takes into account the real conditions, i.e. efficiency and friction losses in the worm and planetary gears. The choice of motor power was done on the basis of the analysis of energy consumption during walking.[13] An average motion speed (about 0.05m/s) related to the mentioned motors speed was assumed. The considered weight of the LAVA was 19.6N (2kG) and body height 0.14–0.16m (with the length of leg links 0.08m and 0.09m). For a calculation of the energy consumption of the walking machine we ignored the friction losses in the leg joints, the limited efficiency of the actuating system, the environment resistance and the soil deformation losses. The knowledge of the horizontal reaction force distribution during insect locomo-

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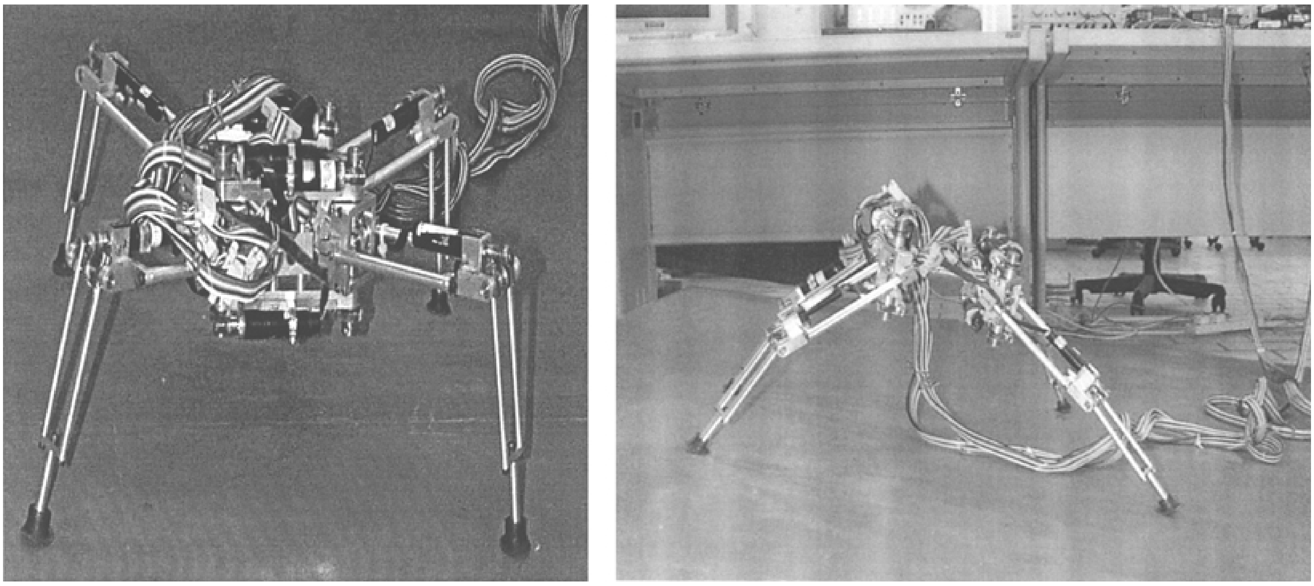

Fig. 3. LAVA in different configurations.

tion[14] and the worst case (extreme case) were taken into account (the reaction forces were scaled proportionally to the LAVA weight). The joint torques were calculated using the Jacobian method:

$$\tau = J(\theta)^T F \tag{1}$$

where $J(\theta)^T$ is the transposed Jacobian matrix (evaluated for the LAVA leg kinematics), F represents the force vector exerted by the leg, with the vertical component supporting most half of the body weight, and τ is the vector of joint torques. The applied method of motor torque and power calculation (worst/extreme case) yields an overestimation. On the other hand, we neglected the limited efficiency of the mechanical and actuating system (the motor efficiency is in the range of 80%, and efficiency of the gear heads is 70%; friction and other sources of energy dissipation were neglected). On the other hand the energy saving resulting from the self-locking action in the support phase was also neglected. As a result of calculations we selected the 4.5 and 3W motors, as mentioned above. The walking abilities of the LAVA confirmed that choice.

3.2. *Differential mechanism and energy/torque demand*

The self-locking feature contributed significantly to the torque required during the leg support phase. In the LAVA, the torque from the motor is utilised mainly to power the, body motion and not to support the body weight. If the mechanical components are precise and are assembled well, the self-locking is "more" active. Figure 4 shows the expected torque demand in a quadruped crawl gait calculated using the Jacobian method.[1] The horizontal axis is scaled in units of simulation time (calculation step), the support time is between the 9th and the 21st calculation step. In our prototypes this time takes 28 to 100ms. In the figure, the torque required to support the body and to power the body motion were differentiated. The largest torque required (Figure 4 – line with circles) was for the support of the body. With an ideal self-locking mechanism in place, this torque demand can be fully neglected, and (in hip joint) we need to consider only the torque consumption to power the body translation. Assuming the self-locking mechanism to be highly effective, we can conclude that, if – in the design phase – the motors are chosen to deliver also the supporting torque, a surplus torque capability will result. In LAVA this torque instead of supporting the machine (and nominal load) itself can be used to produce the machine motion with an extra payload. In the other words, this torque can be used to compensate for a bigger load which demands a bigger body motion powering torque. In the classic legged vehicle design, this is not achievable. In practice, the self-locking mechanism does not approach 100% efficiency, and the mechanical efficiency is limited, as mentioned above. Moreover, the body motion powering torque significantly increases when walking on uneven terrain or when walking by a turning/side motion in comparison with a quadruped crawl gait over a horizontal flat terrain. Therefore, during the estimation of the motor parameters, it was decided (for the LAVA design) that the demand for torque supporting the weight of the body will not be ignored. The experiments with the LAVA's different gaits over different surfaces (with an inclination up to 15°) showed that the motors and reduction ratios were selected properly. Moreover, the current prototype of LAVA has an improved self-locking ability, and we have noticed that this increased the mechanical efficiency when compared with the first prototype version. The payload of the revised version walking over a flat terrain was bigger than that of the first version (up to 50% of the machine's weight).

3.3. *Differential mechanism and walking machine speed demand*

For the sake of comparison, in this section, we will assume that the reduction ratios are equal in the classic design and the design utilising the differential gear. Figure 5 (left) shows the joint angles during the leg transfer (when the angles change is biggest). The angles were calculated for the typical leg-end trajectory implemented in the LAVA control system (this trajectory is rectangular in relation to

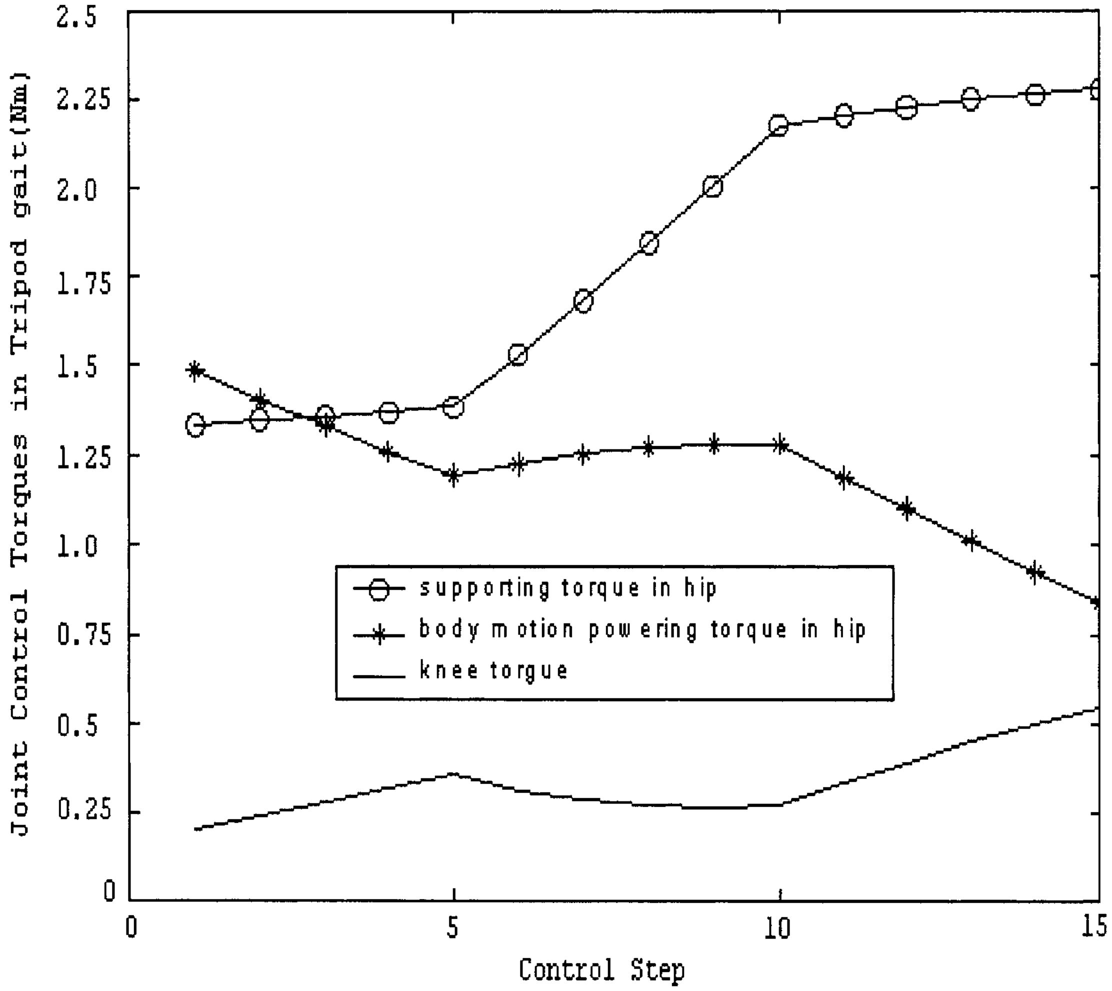

Fig. 4. LAVA (2 kG) torque demand during quadruped crawl: for the most loaded leg.

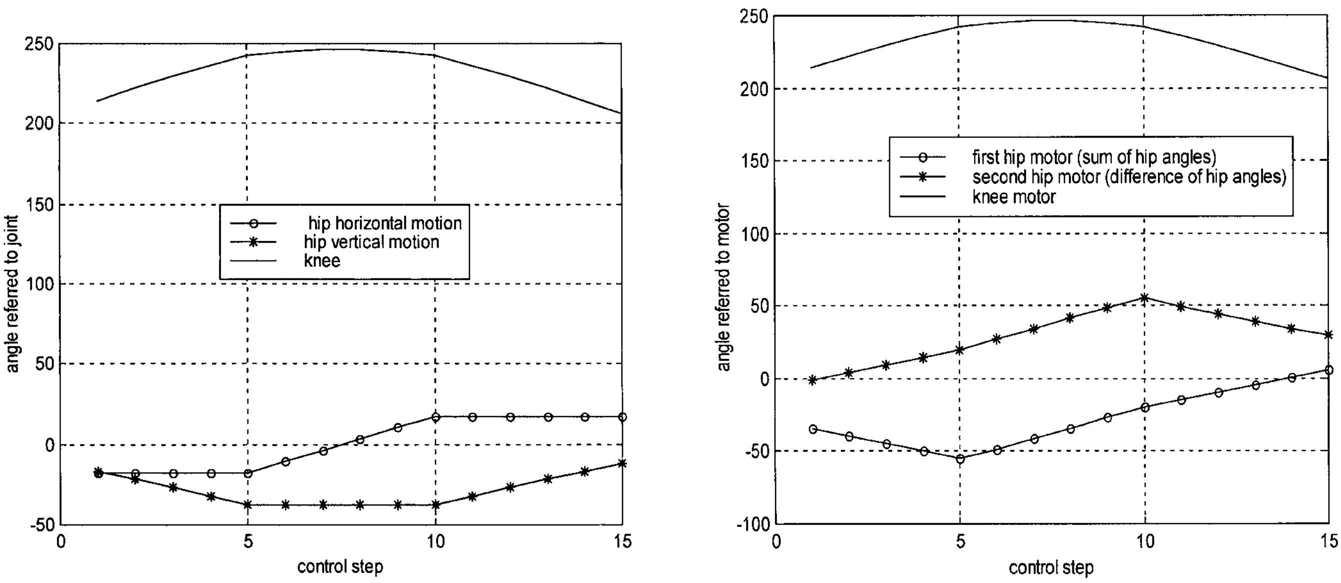

Fig. 5. Leg transfer – change of: joint angles (left hand side), angle caused by motor rotation, and here – *sum of hip angles* for one hip motor, *difference of hip angles* for the second hip motor (right hand side).

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the hip). As the leg direct and inverse kinematics problem is very simple (3-DOF) we will not provide the formula here. In Figure 5 we can notice that the knee angle change is from 220° to 240° and back to 220°, i.e. the total range of change is 40°. The angle related to the thigh horizontal motion changes from –20° to about 20° thus the range is equal to 40°. The angle related to the vertical motion changes from– –20° to –40° and back to –20°, hence the range of change is 40°. In the differential mechanism one of the hip motors follows the sum of angles and the other hip motor follows the difference of hip angles. As a result, one of the hip motors (depends of the sign of the angles) must move with a velocity greater than expected in the classic hip design.

In our design (Figure 5 – right hand side) the range of the knee angle change (and the expected motor speed) is the same as in traditional design, but one of the hip motors must produce the change from –30° to –55° and to 5° (thus 80°) and the second hip motor – the motion from 0° to 55° and back to 30° (thus again 80°), (see Figure 5 – right hand side: the second hip motor).

We noticed that in the majority of implemented gaits, one of the LAVA hip motors is expected to produce the angle change up to 2.7 times larger than that in the classical design, where separate motors actuate separately forward/backward and upward/downward thigh motions. Assuming that the time of this change is the same as in the classical design (the same walking speed), it can be concluded that the speed expected from the motor in the differential mechanism can be 2 to 3 times greater than that for the motors in the classic design. If the motors are working at a maximum possible average speed, the classically designed machine will move at least at twice the speed of LAVA for the same gear reduction.

However, it should be noticed that there are other factors than the leg design limiting the body travelling speed, e.g. the number of leg steps which must be completed to cover the given body translation. If the leg step length (the range of leg-end backward shift in relation to the body in one support phase) is shorter, the number of steps over the prescribed distance increases, thus increasing the time spent in the ineffective transfer phase (raising up and moving down the leg). Hence the step length should be long to compensate for the time lost on the leg transfer. However, a large increase in the step length will cause posture instability, especially when walking on an undulating or soft terrain.

4. MOTION ABILITIES

Due to the large joint work space LAVA can employ a variety of configurations (insect, reptile, mammalian, etc.). Moreover, front legs can serve as manipulators (Figure 6).

LAVA has the potential to overturn. Such a feature is useful when the device is used for exploration. Scientific instruments like probes, sensors etc. sometimes cannot be located symmetrically on the body of the vehicle, because of their cost or weight. If during a mission, a robot topples over and falls down with its back on the ground, it should be able to get up and return to the normal position. In the control system development one of the tasks was the design of a series of steps so that LAVA could flip onto its other side. We used "unbalanced weight" for motion stimulation. The body was lifted and then made unstable by moving the CoG (Centre of Gravity) outside the support polygon. The torque produced by the motors, plus the torque resulting from the "unbalanced weight", pulled the body to the next position. Two sequences of LAVA overturn motions were designed. The first sequence mainly makes use of the "unbalanced weight" to topple over, therefore in a series of motion steps the main body is raised and then the static equilibrium is lost by moving the CoG out of the support polygon (Figure 6 – left hand side). In the second sequence not only the "unbalanced weight" of LAVA, but the bigger torque exerted by the knee motors produces the toppling effect. The drawback of the first solution is the body impact when falling over during the transfer from posture 7 to posture 8. In the second solution, the torque produced by the

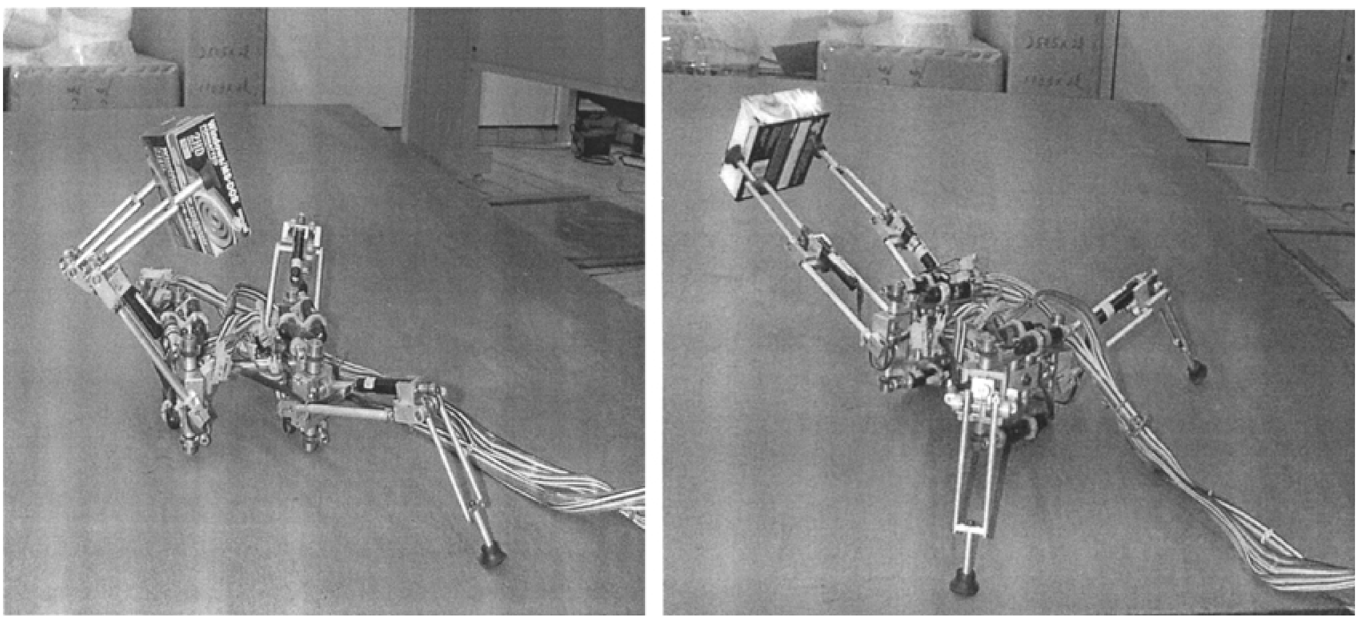

Fig. 6. Lava picking up a diskette box.

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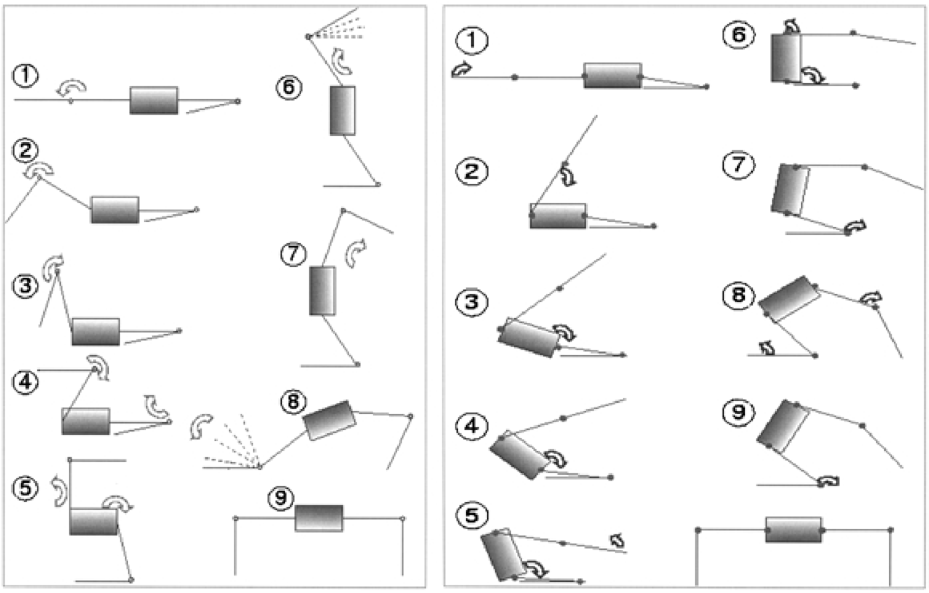

Fig. 7. LAVA posture during the overturn motion: left hand side – motion with impact, right hand side – motion without impact but with bigger torque produced by the knee motors.

knee motors is bigger than in the first sequence, but as it was tested (despite preliminary calculations), the motors are still able to topple over the body. Based on the observation it was decided that the LAVA impact should be avoided and the second solution was selected for use (Figures 7 and 8).

5. CONTROL SYSTEM: REMARKS

The control system will not be described in detail in this paper as it is given in other publications.[15] Here we will only add as yet not described system features. At the executive (joint) level we use universal motor PID controllers with position feedback delivered by encoders. The controllers are working as the peripheral devices of an industrial PC. A QNX real-time operating system with Watcom C is used as the software platform. The motor controllers are receiving the reference data from the PC through input/output ports. The host PC is running concurrent processes responsible for diverse tasks. They communicate with each other only when specific events occur. At the "lowest" level there is the so-called *driver* process, which is responsible for communication with the PID controllers (it sends the reference data when the previous reference is attained). The *driver* continuously monitors the PID controller status register, and when the commanded position is attained it loads the next reference data for all of the 12 motors. The *driver* receives the target data calculated by the gait generator which is located in the *leg* process. The *leg* process is responsible for the communication with external sensors (i.e. leg-end force sensors for compliance force control),[13] generates the gait, calculates the joint reference position (expressed in encoder counts) and sends the data to the *driver* only when the *driver* is informed by the executive level (PID controllers) that the previous position has been attained. Figure 9 illustrates the *leg–driver* inter-process communication. *Leg* uses the QNX **send** command, which suspends the *leg* until the *driver* responds (with the **reply** command), informing that the previous target has been attained. In the event that hardware (joint controllers, motors) are too fast, the *driver* would have to wait for the *leg* process suspended on the **receive** command. In reality, this is not possible as the proper timing is enforced by proper motor velocity profiling and adequate choice of motor accelerations executed by the joint controllers. The **send**, **receive**, **reply** co-operation is organized in such a way that the *leg* calculations of the data for the next control step are realized when the motors are in motion completing the previous step. At that time *leg* and *driver* perform independent action. The *driver* monitors the controllers' status (in position). The *leg* process is faster than the hardware and when the calculations are ready, it sends the data to the *driver* (**send**). The *driver* receives the data

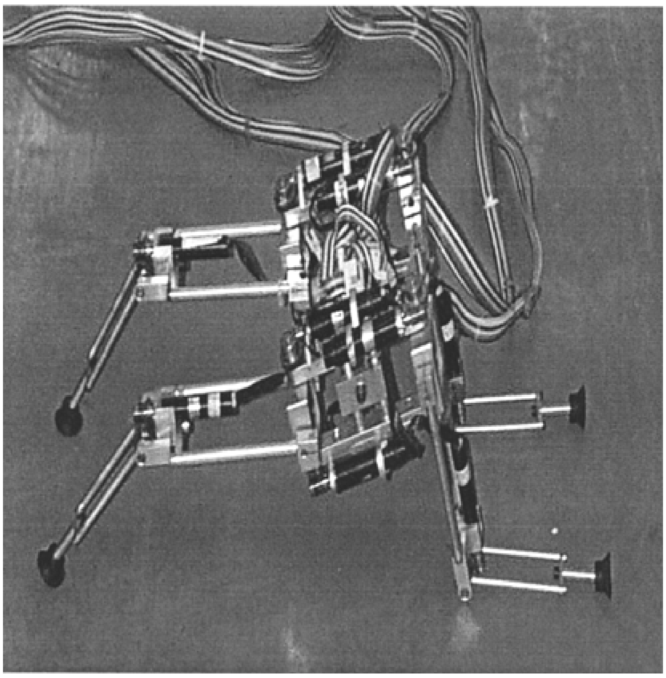

Fig. 8. LAVA between postures 9 and 10 (motion scheme from the right hand side of the Figure 7).

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(**receive**) and will release the leg for further calculations (using the **reply** command) only when the previous step has been successfully completed and the data for the new step have been properly loaded into the controllers. This scheme is very effective in implementation, especially when in each control step the leg-end trajectory can be modified due to the external conditions (i.e. leg force control).[15]

The data package that is being sent from the *leg* to the *driver* process has only 25 bytes. The first item (see Figure 9) is the command status code (cs_status) which tells the *driver* what to do. On powering up the *leg* sends the initialization command (INIT) which, in turn, stimulates the *driver* to initialise the controllers (the *driver* sends the demand to reset internal registers and loads the PID controller parameters). The SYNCHO command causes leg synchronization in which the *driver* allows the programmer to synchronize the leg positions using the PC keyboard. Synchronization is done leg-by-leg. The MOVE command produced by the *leg* process transfers the reference data to the *driver*. For the first control step in the motion sequence the MOVE operational code is supplemented by the constant FIRST, thus causing the *driver* to set the accelera-tion for the trapezoidal profile of motor velocity. When the control step is consecutive one MOVE is supplemented by the NEXT constant. For the last control step when the *driver* shouldn't monitor whether the next data is loaded from the *leg* – the MOVE is sent together with LAST constant. These operational codes are followed by the leg number(leg_no) and the coded information stating whether the motion is relative or absolute (rel_abs variable) and finally the reference data. If the data pertains to all legs(i.e. normal walk) then the leg_no variable contains a special code which means that the data is for all legs. In this situation the *driver* process will expect the data for 12 joints. For other motions (i.e. manipulation – when only selected legs are moving), the MOVE command is supplemented by the number (index) of the leg to be moved. When the motion of several legs is expected in the time, (e.g. two legs), the MOTION commands with adequate leg indices and data are sent several times (e.g. two). The LAVA legs are indexed from 1 to 4, but the software was written is such a way that the total number of legs can be set up to 8. It is possible to stop the motion (of all legs or one leg) immediately by sending from the *leg* process a STOP command.

Leg can also ask about the current leg position (by issuing the GET_DATA command). In that case the *driver* transfers

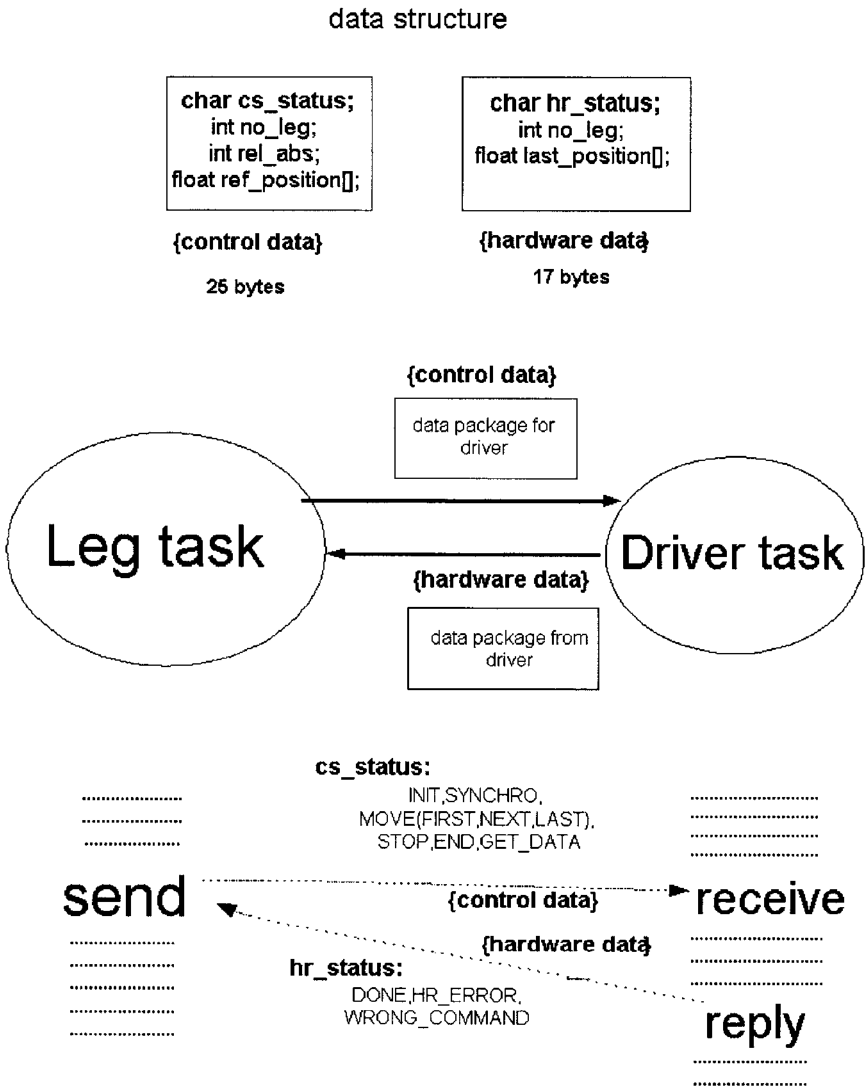

Fig. 9. Leg – driver communication.

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this request to the controllers and responds by DONE, supplemented by the current position received from the encoders (through the joint controllers). The *driver* sends to the *leg* process a package of up to 17 bytes. Its head contains the hardware status (hr_status), i.e. DONE (the target position for previous control step is attained or current position has been recorded), HR_ERROR – when a hardware error occurred, or WRONG_COMMAND when the command received from the *leg* process (cs_status) is invalid (not from the command list).

6. CONCLUSION

The LAVA control software is still under development. Several different gaits were implemented[16] (quadruped crawl forward, backward, side walk to the left, to the right, turning motion, motion over inclination, motion over stairs).

Up till now the problem of proper design of the feet was neglected. In the 3 degrees of freedom design the leg-end orientation cannot be controlled. Currently, the rubber cylindrical feet are affixed to the legs. This results in high friction during motion and therefore produces energy losses. In much bigger and heavier GROVEN machines with the same design idea the feet are attached to leg links by passive universal joints with springs.

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