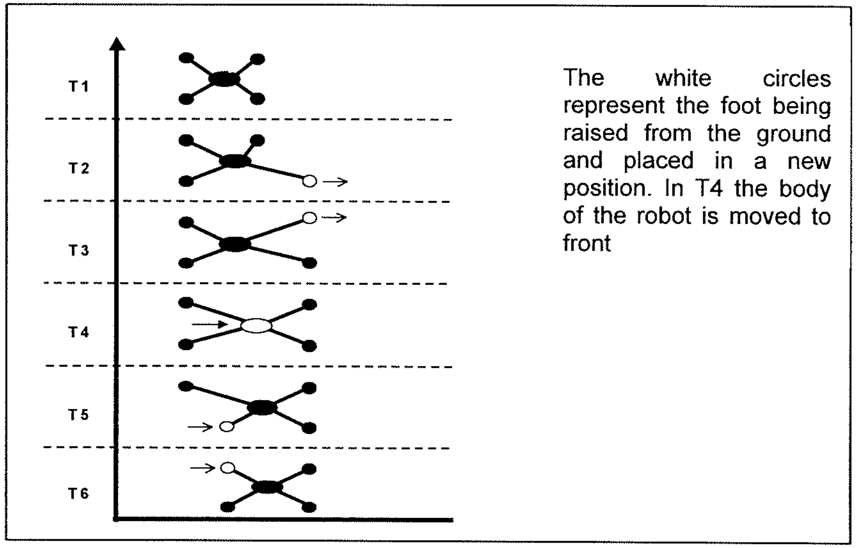

Fig 8. Climbing gait

6. Conclusion

This paper outlined the design of a leg, which can overcome the singularity problem by avoiding the rotation axis from falling in the same direction. The Jacobian discussed in this paper can be easily converted into software to be used in any applicable computer. The leg kinematics may seem tedious but it is simple enough for practical implementations to achieve a good kinematics control. The robot is being constructed while this paper is written.

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A Six-Legged Hybrid Walking And Wheeled Vehicle

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Abstract

This paper discusses the mechanics and control specifications of a hybrid walking and wheeled robot currently being built at the Curtin University of Technology, Western Australia. The vehicle, called the "Hydrobug", is designed to transport three adult passengers over extremely rugged and broken terrain in "walking mode", and when commanded, it will be able to travel quickly over relatively smooth roads and surfaces in "wheeled" or 4-wheel-drive mode. The need for high speed, low cost and useful large scale walking vehicles is highlighted, followed by a brief discussion of the main mechanical design concepts, hydraulic circuit and control architecture for this new type of hybrid walking and wheeled vehicle.

Keywords:
Walking robot, adaptive suspension vehicle, hydraulic servo control, adaptive gait, 3D computer simulation, real-time rendering

1 Introduction

There is an enormous variety of walking robots in the world today. Most of them have six legs to maintain good static stability, many have 8 legs for greater speed and higher load capacity and there are some that implement clever balancing algorithms which allow them to walk on two legs to move over sloping ground and to climb up and down stairs, like humans do (eg. the HONDA robot). In general, the main motive behind the creation of most of these walking machines is to have fun learning about the physics of motion by applying "state of the art" technologies to control the movement of articulated limbs and joint actuators. After all, it is not an easy task to recreate the efficient yet very complex movements of biological insects and mammals which effortlessly execute various types of periodic gait patterns and adaptive gaits and very high speeds. (Visit the CLAWAR web site to view most of the modern walking robots that have been built in recent years).

Unfortunately, due to the very complex and multi-disciplinary nature of this field of research, very few walking robots and multi-legged vehicles have been proven to be the "best and most economical solution" for solving problems in domestic, industrial, construction, military or space applications. It seems as though most of today's small walking robots are only useful for modelling or entertainment value. Also, the majority of large scale 'high-powered' walking robots are still in their "experimental" stages and are not commercially available for bulk purchasing. Most large scale walking robots lack sufficiently intelligent software for solving "real-world" problems automatically and in the most cost-effective manner possible. With the added flexibility of being able to control the foundation points of the vehicle while traversing over almost any type of irregular surface, comes the increased complexity of foot and joint control to maintain stability and coordinated movements for gait movements. Another major problem is the inherent slowness of legged and walking locomotion, compared to wheeled transport. It would be beneficial for a mobile robot to possess the advantages of extreme rough-terrain-negotiating flexibility, which multi-degree-of-freedom (MDOF) legs can offer, with the high speed and simplicity afforded by wheels. Such a multi-legged and wheeled robot would be able to find practical use in solving difficult transportation type problems in virtually any type of outdoor application where high speed is essential.

Some examples of useful applications for reliable, high speed, and high-load-carrying capacity walking vehicles include:

- A walking vehicle for paraplegic people or the elderly who cannot walk easily
- Deep sea or planet surveying and exploration on the moon or on Mars
- Automated or tele-remote controlled (semi-automated) construction
- Underground mining
- Automated agriculture (planting and harvesting) eg. Plustech foresting robot
- "Battlebots" to take the place of human soldiers on a battlefield
- Security or police robots that can patrol a defined area and identify or apprehend trespassers
- Firefighting robots that can climb over rough terrain and large obstacles to reach the heart of a fire with a fire extinguisher or water hose.
- Skeletal animatronic machines to take the place of "fake-looking" 3D computer-generated dinosaurs in monster films and science fiction movies.

The Curtin University "Hydrobug" project involves the design, construction and testing of a 6-legged "insect-like" hybrid walking vehicle which will be able to carry three adult passengers over rough terrain or very broken ground with gaps, pot holes or obstacles which are too large for wheels to traverse. This vehicle is also designed to continue moving from level ground onto steep inclinations up to 45° to the horizontal. The Hydrobug is designed with the necessary degrees of freedom to walk over extremely rugged terrain using 6 three-degree-of-freedom articulated-limb legs. It will also be able to convert to 4-wheel-drive mode for high speed travel, while its legs are fully raised and its feet are kept high off the ground. This type of robot will be able to travel at high speeds on smooth roads.

This paper describes the operating principles for the legs, wheels, hydraulic circuit and control systems of the Hydrobug and presents some control methods for effective "low level" control of the feet and the wheels. Since it is currently under construction, these theories still need to be tested and results of such testing will be published in future papers relating to this project.

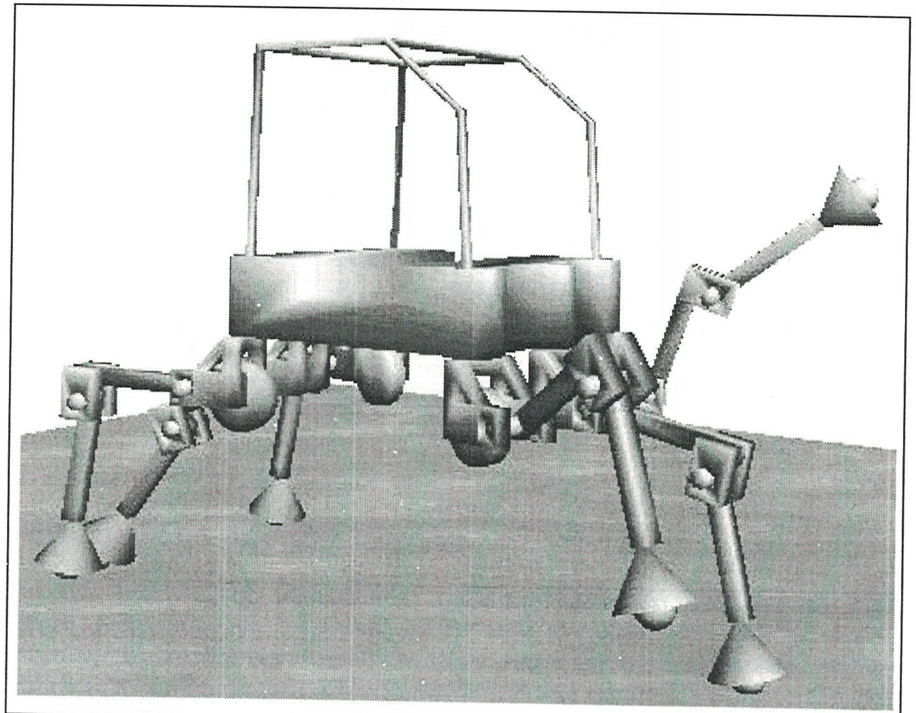

Fig 1. Simulation of the Hydrobug using Visual C++ and Microsoft Direct3D®

2 Mechanical design

Figure 1 shows the general layout of the six legs and four underbody wheels of Hydrobug design. Each leg has three active (controlled) degrees of freedom (dof), driven by servo-hydraulic pistons, and one passive degree of freedom at the hip, being the spring and air-damped suspension system, which will absorb vertical shock during walking and wheeled locomotion. Hence, each foot will be allowed to move independently of each other within an extremely large 3D workspace. The serially-connected links provide the yaw, pitch and pitch (YPP) degrees of freedom for climbing up steep hills or around corners.

One wheel is attached to each outer corner leg at the hip joint fork. Independent steering for each wheel is achieved by controlling the yaw actuator (hip rotation piston) of the leg that the wheel is attached to. This occurs during "wheeled mode" when all feet are raised high off the ground and the four underbody wheels support the entire mass of the vehicle. Each of the four wheels is independently driven by a Parker® TD045 hydraulic motor, for full-time four-wheel drive. The Hydrobug's actuators, wheels, hydraulic pump, valves and 20 HP engine were selected so that it will be able to travel at a maximum level ground speed of 5 km/hour in walking mode, and up to 50 km/hour in wheeled mode.

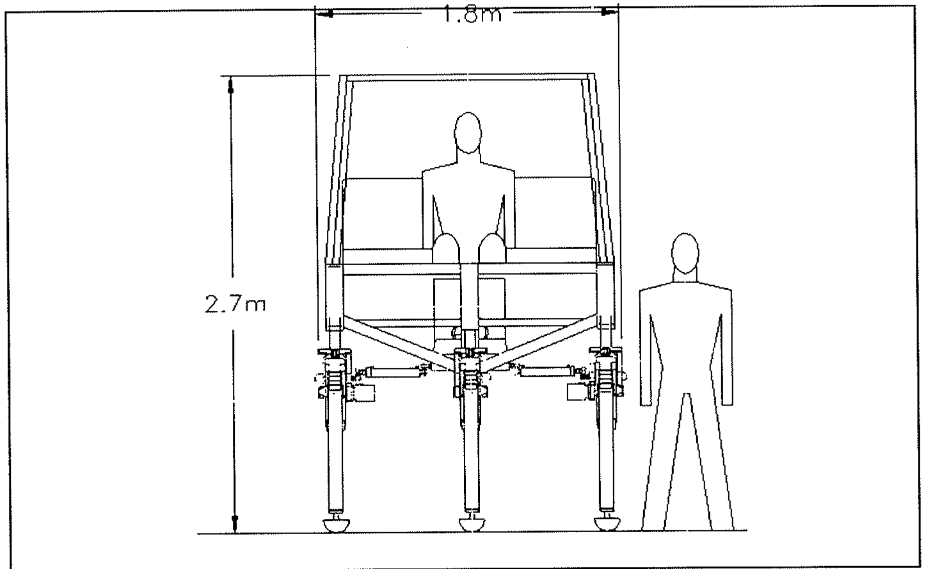

Fig 2. Front layout view of the Hydrobug

The total mass of the walking robot, which includes a payload of three average-sized adult human passengers (3 x 80 = 240 kg), will be about 450 kg. It's overall dimensions are approximately 3.3 m average length × 1.8 m wide × 2.7 m tall.

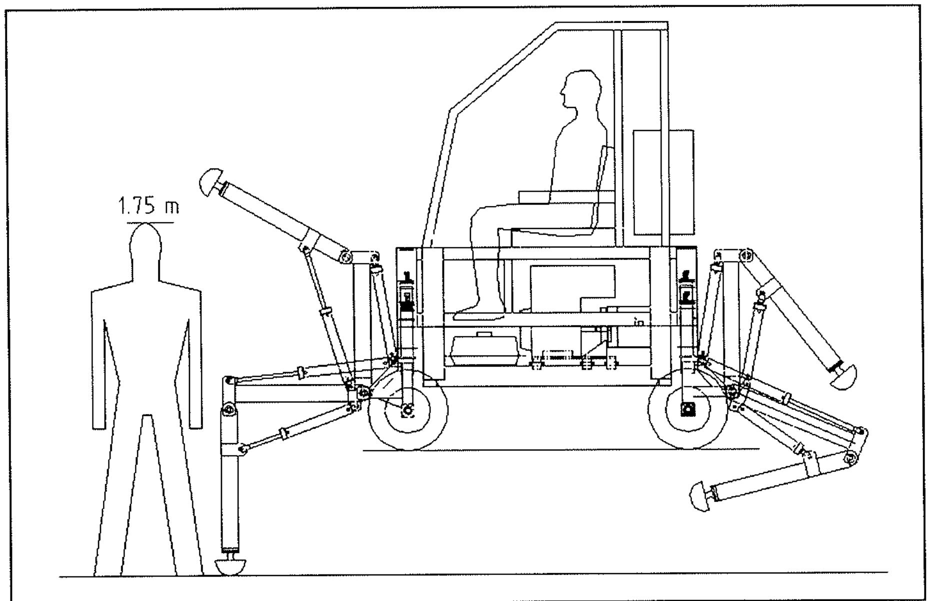

Fig 3. Side layout view of the Hydrobug showing extreme foot positions

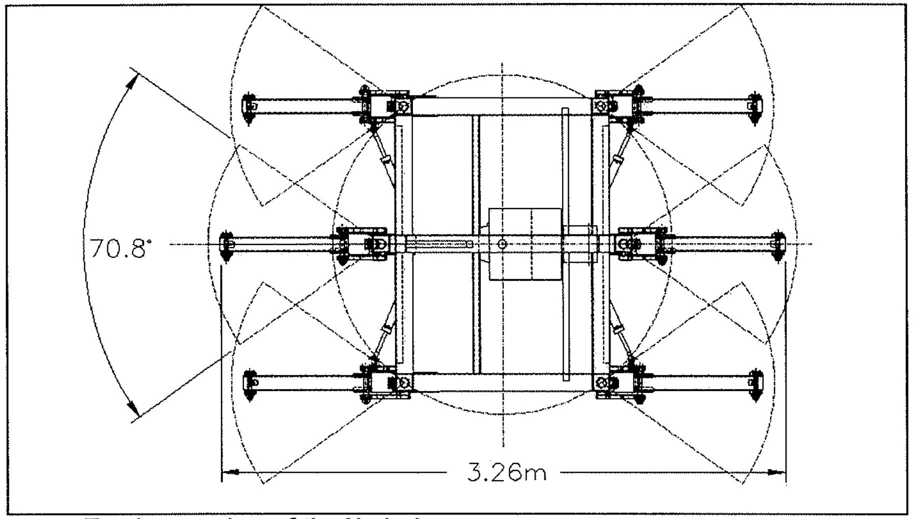

Fig 4. Top layout view of the Hydrobug

Each wheel of the Hydrobug has a steering range of 35.4° left and right, hence, wheels may lock to these extreme angles to enable rotation on the spot for fast changing of direction without the vehicle centre changing position. In normal driving mode, the control of the steering angles and speeds for each wheel will be governed by the distance and direction of each wheel relative to the "centre of curvature" (COC) for the turn. From a top view, if a radial line is drawn through the vertical steering axis of a wheel to this COC axis (which is common to all 4 wheels), the steering direction of this wheel must always be aimed perpendicular to this radial line, and the speed of rotation of this wheel must also be in proportion to its distance away from the COC axis ie. the closer a wheel is to its centre of curvature, the slower it must rotate and the sharper its steering angle must be. This is important to prevent wheel drag, excessive tyre wear and high structural frame stresses which may be caused by mismatching ground speeds of any wheels. A hydrodynamic braking system will be implemented for each motor along with pressure relief valves to prevent backpressure, generated during braking, from damaging hydraulic lines and mechanical components. Wheel rotation will be provided by Parker® TD045 45cc/rev (800rpm max) hydraulic motors driven by Parker® 22LPM (max) bidirectional 5/3 way proportional solenoid valves. The front and back wheel rotation speeds are proportional to the distance of their respective steering axes (located at the corners of the body in Figure 5) from the COC. For straight driving, the COC axis will be at an "infinite" distance to the left or right of the mid-length position of the robot body. For turning left, the COC axis will be at a finite distance to the left of the mid-length position of the robot body, assuming that both front and rear wheels turn equal but opposite angles, respectively. To steer right, the COC will be to the right of the body. The sharper the turn, the closer the COC will be to the robot body, as illustrated in Figure 5.

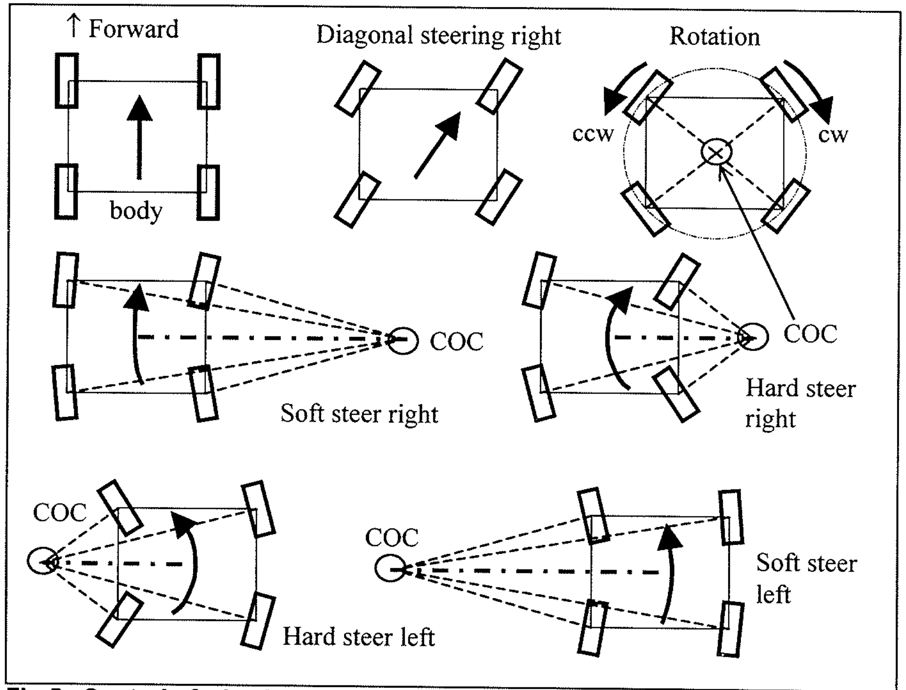

Fig 5. Control of wheel directions with a common "Centre of Curvature" COC

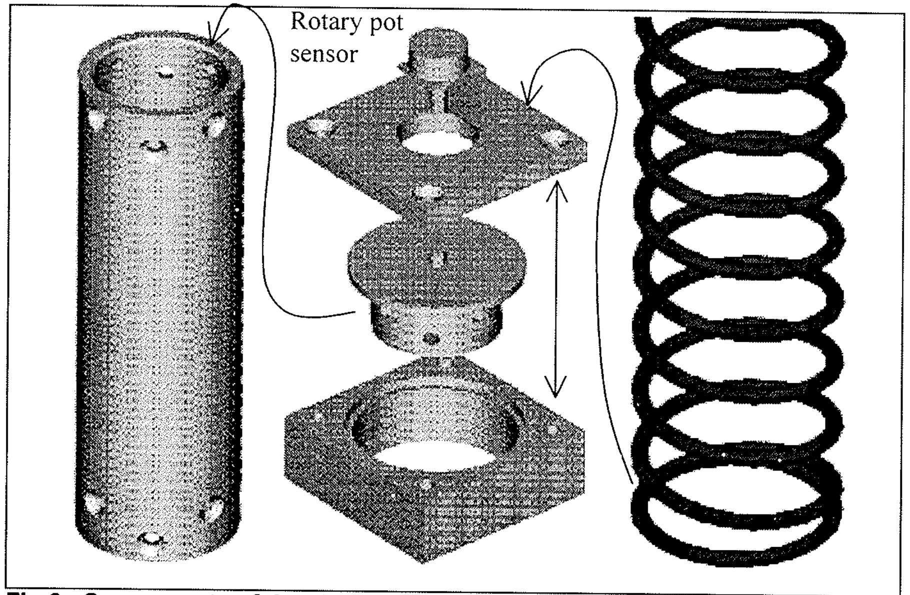

Fig 6. Components of the air-damped wheel and leg suspension system

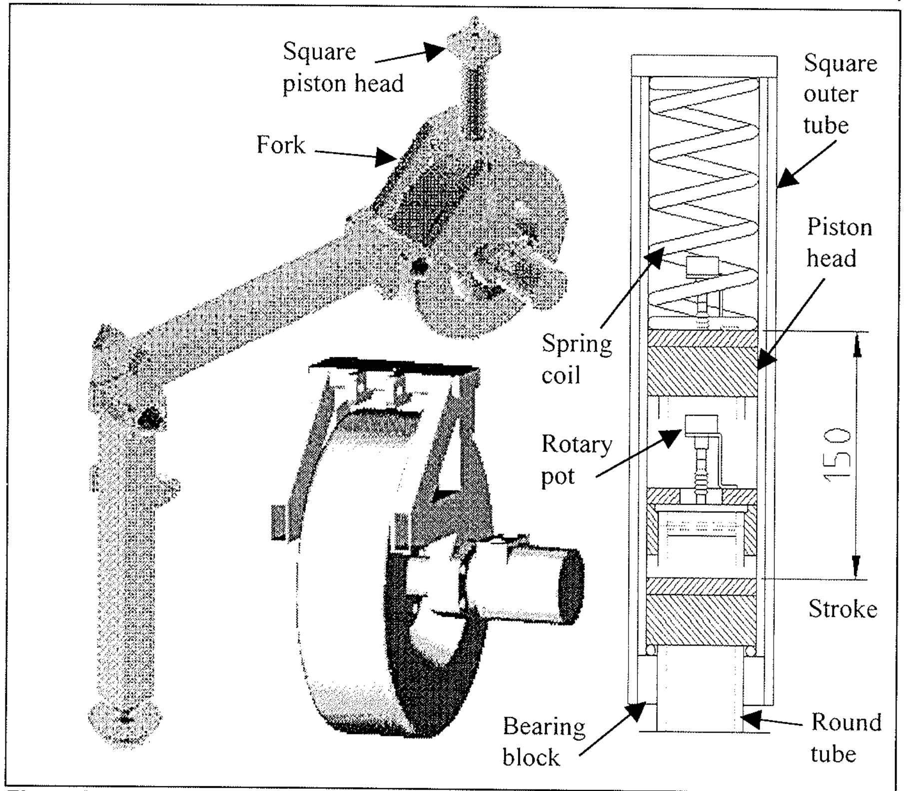

Fig 7. Hybrid "leg-wheel" design showing fork, motor and suspension

Figure 6 shows the disassembled components of the wheel suspension system. The design objective for the hybrid leg and wheel system was to minimize the number of actuators required to control the necessary degrees of freedom for the task, and to minimize the number of components to keep weight to a minimum and to keep construction costs low. Hence, the leg hip and wheel share the same "steering" axis and actuator, as well as the same suspension system. The most difficult problem encountered in completing this design was in finding an effective and reliable way to measure steering angle rotation accurately while the entire fork translates in the vertical direction due to the passive (suspension) degree of freedom. Such a sensor arrangement was not allowed to have fast wearing parts which would result in large backlash inaccuracy. The suspension system consists of a plunger (syringe-like) square-sectioned piston which moves vertically against a custom-designed suspension spring above it. Damping can be achieved by setting a throttling valve to vary the flowrate of air from one side of the piston head to the other. The actual "rod" of the plunger is made of a round hollow aluminium tube which is free to rotate to provide the "yaw" (steering) degree of freedom for the fork. The rotary sensor body is mounted on top of the non-rotating square sectioned piston head and the sensor's shaft is coupled to the round rotating tube.

3 Hydraulic circuit design

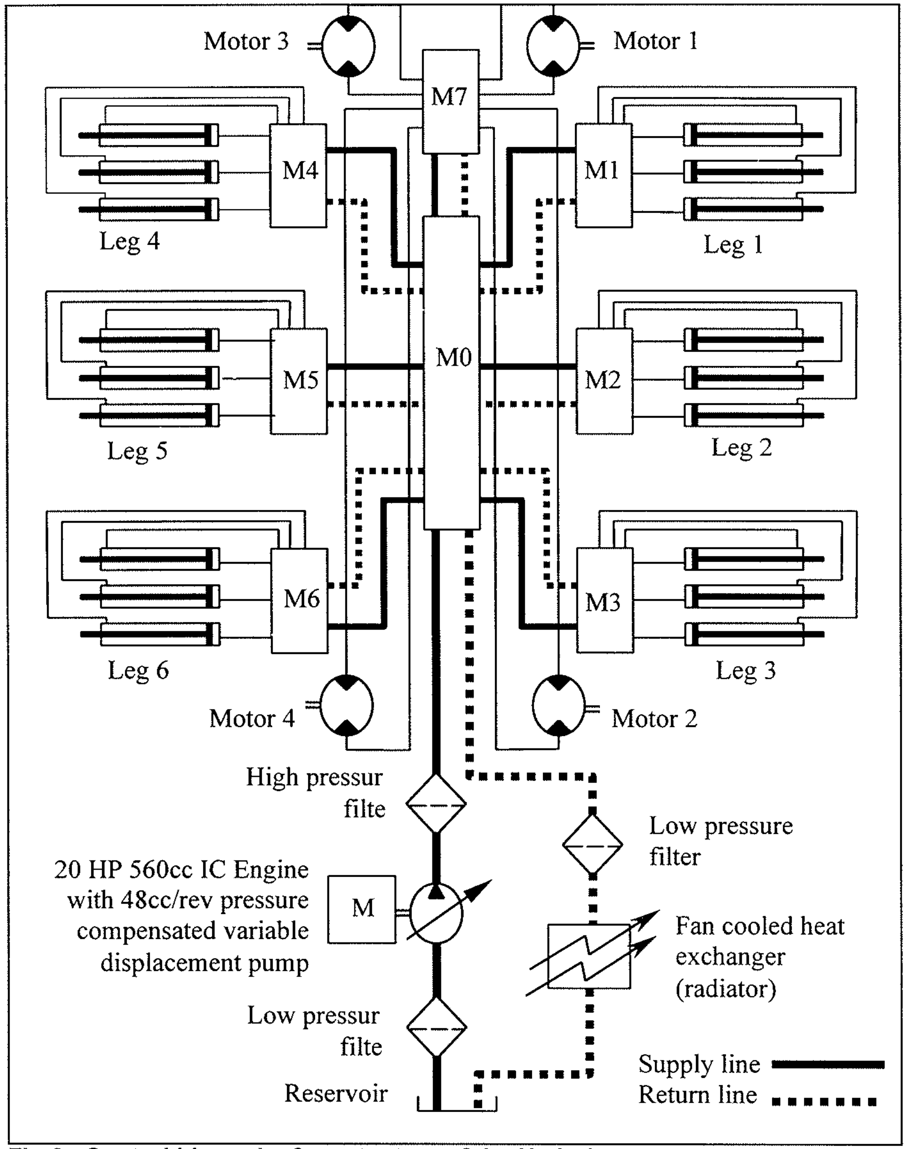

Fig 8. Control hierarchy for actuators of the Hydrobug

The basic layout of the hydraulic circuit of the Hydrobug is shown in Figure 8, without the detail of the hydrodynamic braking circuits. A 20 HP petrol engine driving a 48 cc/rev pressure compensated variable displacement pump will provide a system pressure of about 110 Bar and will deliver a maximum flow of 123LPM to all 5/3 way proportional solenoid valves mounted on all manifolds (M0 to M7).

4 Leg kinematics and control

The Hydrobug serial-link leg has three actively controlled and independent degrees of freedom for positioning its foot (frame 3) in cartesian space, (x, y, z), relative to its base frame (frame 0). Using the Denavit-Hartenberg convention, the forward kinematic equations of the leg are:

$$x = \cos\theta_1 (l_3 \cos\theta_2 \cos\theta_3 - l_3 \sin\theta_2 \sin\theta_3 + l_2 \cos\theta_2) + l_1 \cos\theta_1 \quad (1)$$

$$y = \sin\theta_1 (l_3 \cos\theta_2 \cos\theta_3 - l_3 \sin\theta_2 \sin\theta_3 + l_2 \cos\theta_2) + l_1 \sin\theta_1 \quad (2)$$

$$z = l_3 \sin\theta_2 \cos\theta_3 + l_3 \cos\theta_2 \sin\theta_3 + l_2 \sin\theta_2 + d_1 \quad (3)$$

The above equations have been used in a new blind-search numerical "inverse kinematics" algorithm to solve for the joint angles θ_1, θ_2 and θ_3 to achieve a given foot position (x, y, z) relative to the base frame of the leg. [1]. These angles are determined by the stroke positions of the hydraulic pistons, which need to be controlled by six slave microcontrollers (one BasicX-24 to control each leg, 4 of which control the speeds for individual wheels). All slave microcontrollers will be attached to a common 38400 baud serial bus attached to a PC COM1 serial port, allowing a Microsoft Visual Basic® (version 6, Win32 platform) Windows 98 program to monitor all important control variables and issue high-level commands to the 6 slave controllers. The driver of the vehicle will operate a "Thrustmaster" style joystick attached to a laptop PC so that the control program will be able to walk the robot in any direction as indicated by the joystick. All high-level gait control and inverse kinematics code will be handled by the PC. All low-level "time critical" servo control functions will be executed by the BasicX-24 controllers (which is also programmed in a clear and easy to understand form of Visual Basic). The BasicX-24 controller has 16 programmable general purpose I/O pins with 10-bit A/D input capability on any pin, and 8-bit pseudo D/A output on any pin. [2]

5 Future research

Future research will focus on trajectory planning, adaptive gait control and 3D simulation and programming using Microsoft™ Visual C++ and DirectX®/ Direct3D or OpenGL. A 3D walking simulation program has been written (see Figure 1), using object-oriented-programming techniques, to model and animate the entire walking vehicle for level surface crawl gaits. Research will also be directed towards using "fuzzy logic" algorithms or "Genetic Algorithms" to generate suitable walking gaits over highly irregular terrain. Such control strategies will aim to maximize the 'stability margin' of the vehicle. This means maximizing the closest distance between the vehicle's 'centre of gravity' vector and the nearest edge of the 'stability polygon', which is formed by the outermost supporting feet as seen in a plan view. The centre of gravity vector must always lie above or within this stability polygon (as seen from a top view) in order for the vehicle to remain statically stable. The actual vehicle body and hydraulic power pack has been completely built. Currently, a prototype hybrid leg-wheel is being fabricated for testing hydraulic servo control schemes for foot position control, wheel steering and wheel speed control tests later on this year. Future papers and progress reports will be published relating to various aspects of this project.

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Actuators and Implementation Issues

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Demands on the knowledge and skill base of the modern engineer continue to increase as the rate of technological advancement steadily rises. However, the traditional discipline boundaries of mechanics, electronics, control, and software can impede the design and development of products, devices and systems. The integration of, and synergism with, these disciplines in the design process is said to differentiate the mechatronics practitioner from "mainstream" multidisciplinary engineering teams. In addition, a healthy balance between "across-the-board" breadth of knowledge and "specialist" depth of knowledge is required in engineering projects.

However, the rapid development and adoption of new technologies in industry are driving engineering courses toward curricula with considerable breadth of content, multidisiplinary approaches and based around working within teams. In many tertiary institutions the traditional mechanical engineering courses are already adopting more electronics, control and software development into their core – to the extent that there are only minor differences between the mechanical and mechatronic engineering disciplines.

It could also be argued that the above attributes should be implicit in any good design engineer and not specific to the mechatronics practitioner. The practising design engineer is faced with these issues on a daily basis. If this evolution of courses continues, the question must be asked: will mechatronics survive in the long term or will it be subsumed by a new breed of design engineers?

Actuators

The design and rapid development of actuators is central to the development of mechatronic systems. The power requirements, speed of operation, physical size issues and control difficulties often manifest themselves in actuator design. Considerable effort has been, and continues to be expended, in this vital area.

The use of magnetostrictive and shape memory materials in pulse-modulated pilot valve actuators for large fluid power values is proposed in the paper by *Vuorisalo and Virvalo.* Basic design calculations are presented that compare piezoelectric and magnetostrictive actuation in a sample valve. The use of such active materials provides relatively high speed, non-contact action, and as these materials become more readily available applications such as the proposed valve will be considered more often.