Feature

The harmonious robot

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Abstract
Purpose – To describe the design methodology and human-centre functionality of the whole arm manipulator (WAM) developed originally at MIT and brought to commercial fruition by Barrett Technology.
Design/methodology/approach – The WAM arm is driven by cable-and-cylinder transmissions, which uniquely exhibits zero backlash with low friction and low inertia, endowing the WAM with good open-loop "backdrivability". Two key benefits of the high backdrivability are: motion control through joint torque control, which enables the intrinsic sensing of forces over the whole arm and makes it inherently safe to humans; operation directly in the Cartesian domain without the need for inverse kinematics calculations, providing very rapid responsiveness as demonstrated in the "baseball robot" of Tokyo University. Another benefit of the WAM is its kinematic redundancy through the 4-dof (degrees-of-freedom) main axes (7-dof with the wrist). Recent major advances in the WAM include the "puck", the world's smallest fully-featured servo-controller that eliminates the need for an external controller cabinet, and a safety circuit that limits, by a set amount, the power flow from the WAM to a person or object while not inhibiting the reverse from human to arm. The WAM's intrinsic force control has allowed the development of software-defined haptic walls, which are being exploited by partners such as the CMU (Carnegie Mellon University) Robotics Institute, in patient rehabilitation, and Mako Surgical, for use in joint surgery.
Findings – The Barrett WAM's good open-loop backdrivability has initiated the development of novel human-centred robot applications that will expand the use of robots outside the factory and into human-inhabited areas.
Originality/value – Presents the design methodology, features and applications of the Barrett WAM human-centred robot.

Keywords Robotics, Man machine interface

Paper type Technical paper

The world's first industrial robot, the hydraulically powered Unimate developed in the late-1950s, was designed as a replacement for human workers operating in monotonous, hazardous or unpleasant environments. It was large, powerful and dangerous such that it had to be ring fenced to protect humans. While this was not a problem in the industrial factory it excluded its use in less structured, particularly human-populated environments. It meant that robots did not find their way into the office, the hotel, the home or the hospital. For that to happen, a completely new concept of robot was needed that would work safely and in harmony with humans.

This was the scenario some 20 years ago when researchers at MIT examined the fundamentals of robot technology to produce a design methodology for robots that were intrinsically safe. The aim was a human-centred robot that would more safely interact with people and its environment. The outcome of this project was the whole arm manipulator (WAM), which has been further developed and brought to commercial fruition by Barrett Technology, based in Cambridge, Massachusetts and marketed under the brand name of the WAM arm (Plate 1).

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The design methodology of the WAM arm differs significantly from that of traditional industrial robots. The latter are designed purely on positional control of the end effector with no concern for the forces being experienced between that effector and its environment. In contrast, the WAM is designed with intrinsic force and joint torque control, enabling it to sense forces over the whole arm – hence the acronym – and not just at the working end.

Backdrivability

One of the most significant differences between the WAM arm and a conventional robot is its inherent, open-loop "backdrivability", a measure of how accurately a force applied at the output, the end effector, is reproduced at the input, the drive motors. Good backdrivability means that a person can manipulate the arm simply by moving the end effector. It is almost impossible to backdrive a position-control robot unless it is converted into a closed-loop backdrivable device by fitting force or torque sensors. However, that raises questions of safety for the operator backdriving the position-controlled robot, problems that simply do not arise with the WAM due to its open-loop backdrivability. It is inherently safe.

It is the good backdrivability that enables the WAM arm to intrinsically sense forces over the whole arm by measurement of the torques being applied by the joint drive motors. In

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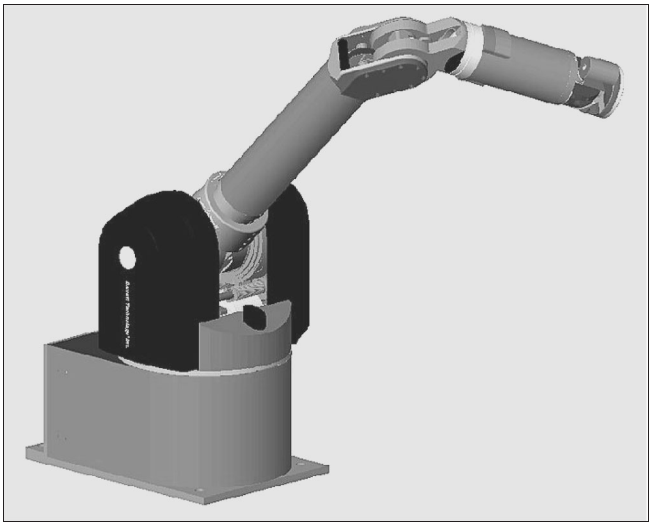
Industrial Robot: An International Journal
Volume 33 · Number 2 · 2006 · 125–130

Plate 1 The Barrett WAM robot



practice, this is achieved by measuring the current in the drive motor windings.

The need to achieve good backdrivability was one of the critical "driving forces" for the work at MIT that resulted in the WAM arm. It was seen as the road to improved control of robots and manipulators with the ability to control forces over the whole arm that would lead to safer operation when working alongside humans.

The obstacles to good backdrivability are inertia and friction in the robot's transmission; reduce these and backdrivability will improve. But, conventional robots are driven through gears and to reduce friction necessitates "slackening" the meshing between the gears, which diminishes accuracy because of increased backlash. In almost all mechanical transmissions – ballscrews, harmonic gears, hydraulics and the like – there is this trade-off between friction and backlash. However, one transmission that does not exhibit this trade-off is the tension-element drive utilising cables or tapes.

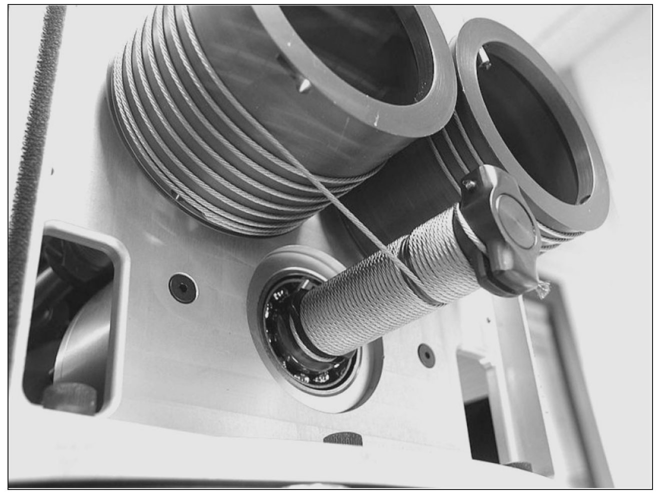
Cable transmission

With tension-element drives there is no backlash and the motion is purely rolling with none of the sliding motion involved when gear teeth mesh. It was this property of low friction with zero backlash that attracted the MIT researchers to design a robot arm driven entirely through cable-and-cylinder transmissions.

Cable transmissions do not have the best reputation for reliability and present some major technical problems particularly for use in robot drives. But, the MIT engineers were able to overcome these hurdles and developed an elegant design for a cable-and-cylinder robot transmission system, which was incorporated into the design of the WAM arm. And, it was this robot arm that was the basis for the floatation of Barrett Technology in 1988 by William Townsend, one of the original team working on the WAM project at MIT.

Ultimately, Barrett launched onto the market 4-dof (degrees-of-freedom) and 7-dof versions of the WAM arm, the latter incorporating a 3-axis wrist fitted to the end of the forearm. The 4-dof WAM arm has a rotary base, a 2-dof shoulder joint and an elbow between the upper arm and forearm. All basic and wrist axes are driven by 1 mm steel cables wrapped around light ceramic-surfaced cylinders (Plate 2) with motive power from rare-earth brushless, high torque-inertia ratio servo motors (Townsend and Guertin, 1999).

Plate 2 Cable-and-cylinder drive on WAM



The motors for the arm are mounted in the base and at shoulder height, but close to the centre plane to minimise joint inertia, while the wrist motors in the 7-dof version are situated in the forearm, avoiding the need to carry the cables through the elbow joint. Because of the WAM's low inertia and low friction, the size of the motors can be kept small, further minimising arm inertia and the low motor inertia further aids backdrivability.

The basic WAM arm was designed as a 4-dof device, as opposed to a conventional 3-dof (6-dof with a wrist) articulated arm robot, to provide kinematic redundancy. Because of this redundancy and because each joint of the WAM is controlled, unlike the conventional end point-controlled robot, the arm can be driven to a variety of poses for any one endpoint position. This enables the programmer to teach both the end position and the elbow pose; for instance to guide the arm through a restricted opening to place or retrieve an object not accessible by direct "line of sight". Should the programmer only control the end-point, the rest of the structure gently complies to external contacts, further enhancing safety. It is a manifestation of the WAM's "whole arm" functionality.

Baseball robot

The significance of the WAM's extremely low friction has been dramatically demonstrated in a "sighted" baseball robot developed at the University of Tokyo by Professor Namiki-san. His team had developed a highly advanced and ultra-fast vision system and thought-up "baseball" as a way to vividly demonstrate the prowess of this system. Initially, industrial robots noted for their high speed and acceleration, were tried. While good at reacting to pre-programmed paths, these failed when the paths were unknown due to the time delay in computing the arm's required movements involving inverse kinematics calculations.

This is not the case with the WAM, as Bill Townsend, Barrett's CEO explains:

> The naturally low friction and inertia in the WAM's drives enables application of Jacobian-Transpose mathematics, which allows operation directly in the Cartesian domain without the need for inverse kinematics calculations.

Industrial Robot: An International Journal
Volume 33 · Number 2 · 2006 · 125–130

> The high friction and inertia in conventional robot drives needs complex and time-consuming offline calculations involving a Jacobian-Inverse.

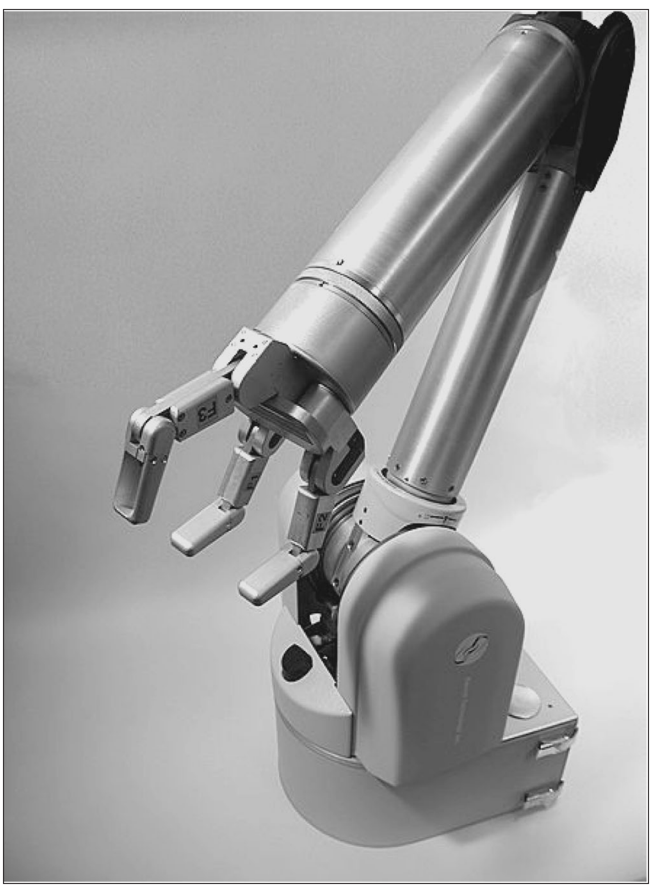
He continues:

> When the ball is thrown the vision system picks up and calculates the centroid of the ball's constantly changing trajectory within 1 ms and then the WAM arm changes (at least begins to) direction within a further 2 ms. At one time, I witnessed at least a dozen throws and the WAM did not miss once, but even more impressive was the ability to aim the ball after striking the bat and hit the target without failure. I'm not a baseball fan but I was stunned!

The unique functionality of the original Barrett WAM arm attracted sales from leading research institutes including MIT, Harvard, Northwestern University and UMass Amherst, as well as from global corporations such as Honda, Ford, Sony, Fanuc Robotics and Z-KAT Medical Inc. These organisations recognised the enormous potential of the WAM's "human-scale" capabilities and are pioneering applications across a diversity of sectors including industry, medical, human rehabilitation and space. At the same time Barrett undertook many incremental developments in the arm to meet the challenges thrown up by new emerging areas in robotics.

Then, four years ago the pace of development underwent a step change when Barrett received US$2.5million in funding from NASA, the US Department of Energy, and the US National Science Foundation. This has resulted in a new WAM arm (Plate 3) designed primarily to meet the projected needs of service robotics and mobile manipulation over the coming decade. It employs the same low-friction, zero backlash cable-and-cylinder drives, albeit with many mechanical improvements, but has completely new and revolutionary electronics that solve many critical safety issues as well as enhance arm performance.

Plate 3 The new WAM arm developed with funding from NASA, The US Department of Energy and the US National Science Foundation



Power flow

Safety is of paramount importance for human-scale robotics and naturally this was the number one area of improvement for WAM2. The concept employed is to limit the amount of total power flowing into the robot as a system to a level that will not harm a human. Although there is no precisely defined level above which it becomes dangerous, power in the 100s of watts exceeds human-scale capability, so Barrett aimed for a safe level of 20-100 W. While monitoring and managing the total energy flow to keep to these limits is simple in concept it is difficult to implement. The size of the problem may be judged from the fact that a conventional robot arm when stationary absorbs in the order of 1,000 W with up to a further 1,000 W under load. To make such devices safe by monitoring variations of just 10 W would be virtually impossible.

As far as dynamic losses are concerned, the WAM arm is highly efficient due to its near-frictionless drives. However, the problem of steady-state losses remains. Consider that in conventional 3-phase motor driven robots the main source of power losses stems from the large external controllers and the hundreds of long connecting cables whose resistive losses are greater than the drive motor windings. In addition significant power is demanded by fans for forced convection cooling inside the control cabinet, where much of the heat is generated by devices providing galvanic isolation to reduce EMI noise.

The main reason that robot control cabinets are large is the need to isolate high EMI emitters, such as servo drives, from sensitive electronic components. While such separation may also provide the space for air cooling, it means that a "common" ground between components no longer exists. The conventional solution is galvanic isolation, circuitry which takes up further space and generates even more heat, compounding the problem by needing larger cabinets and more cooling fans.

By looking at the fundamentals of EMI noise elimination and galvanic isolation, Barrett decided to go in the opposite direction and rather than separate noisy and sensitive components, it brought them as close together as possible. With virtually no separation, the ground really is common, eliminating the need for galvanic isolation, further reducing size. And at such small scale, Barrett could switch to conduction cooling by encasing the controller circuitry in high thermal conductivity, electrically-insulating epoxy.

Townsend says:

> It's always been common knowledge in controller design that you separate noisy components as far as possible from noise-sensitive components if you care at all about EMI effects, as you must in precision servo drives. But, our team discovered that shortening the ground path has a stronger influence on mitigating noise than component proximities have in coupling noise, especially if you include a small amount of well-placed copper shielding. This insight turns controller design on its head; the smaller you go, the lower the EMI effects and the shorter are the thermal conduction paths to the point that you no longer need galvanic isolation. The result is smaller is better and going even smaller only increases performance.

Puck servo-controller

These concepts of size reduction and conduction cooling have enabled Barrett to develop the world's smallest fully-featured brushless servo-controller, measuring just 35 mm diameter by 17 mm high, not much larger than a bottle top, and weighing a mere 43 g. This ultra-compact electronic module resembles a miniature (ice) hockey puck, and hence called a "puck" (Plate 4). The only external part is a 0.2 g, 14 mm diameter by 1 mm thick optically-patterned reflective wheel that attaches to the motor shaft.

A puck has all the features to drive and control a servo motor (as well as undertake other electronic processing functions). It incorporates power supplies, space-vector commutation, laser optics supporting 40,000 counts-per-motor-revolution position encoding, a 32-bit DSP (digital signal processor), a highly precise winding-current sensor, CANbus and RS232 serial communications as well as large volatile and non-volatile memory. Further, it has internal temperature control, motor temperature monitoring, lots of analogue and digital I/O, support for Hall position sensors, strain gauge amplifier and has the ability to automatically adapt to input voltage levels ranging from 18-100 vdc.

In the new WAM arm one puck "services" each drive motor (Plate 5), and for external connections, 44 electrical contacts are hermetically sealed into flutes around the periphery of the epoxy cast cylindrical puck. These flutes provide strain relief to the connecting electrical cables and also can accommodate male pins for attachment to a PCB (described later). Also built into the epoxy casting are alignment features, which augmented by electronics in the laser optics adjusts any misalignment between puck and motor shaft so that the encoder always works first time without the need for shimming.

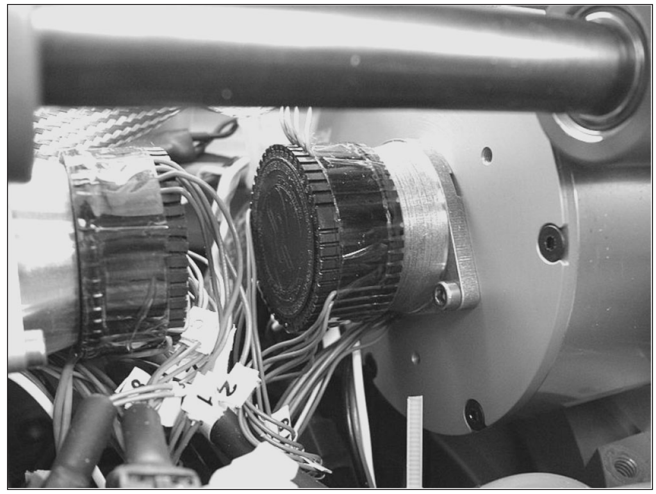
Although small, a puck can pump currents of 10 A RMS peak and 3.3 A RMS steady state with a temperature rise of just 50°C.

Townsend says:

> At 20 W/cm^3, it is the highest steady-state RMS power density ever achieved in a servo controller, with greater than 99 per cent power efficiency. The only amplifiers we have found with higher densities are two-quadrant (not servo) devices driving propellers for model aircraft and the like where servoing position or torque never matter.
>
> The pucks are so efficient that we have run a 4-dof (new) WAM supporting a 4 kg payload and drew only 28 W with a maximum temperature rise of 40°C. To put this in perspective 28 W is the same as 24 (food) Calories/hour, which is roughly what a human arm uses in mild exercise – other robots with a 1 m reach and 4 kg payload require hundreds of watts for the same level of activity.

Plate 4 The puck fully-featured servo-controller developed for the Barrett WAM

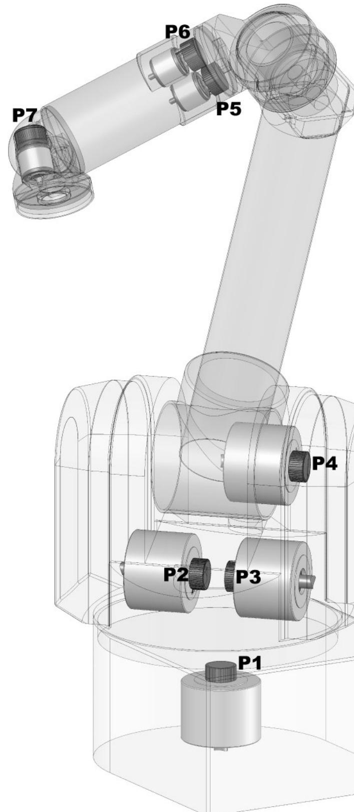
Plate 5 Puck servo-controllers mounted on WAM motors (additional wires shown were only for use during development work)



Safety circuit

With the development of the puck, Barrett was able "in a single stroke" to eliminate the bulky external robot controller. Instead is a network of pucks, one per drive motor (Figure 1), which communicate through the CANbus. The only other

Figure 1 Schematic layout of the new WAM



Industrial Robot: An International Journal
Volume 33 · Number 2 · 2006 · 125–130

electronic module, albeit a critical one, is a small circuit board that performs safety functions and communicates with the teach/operating pendants, and is small enough to fit in the base of the WAM.

This circuit board is central to the safety of the new WAM arm. It limits the power flow from the whole arm to a person or object by a settable amount, such as 50 W, but when the flow reverses from the person to the arm there is no restriction and the full amount passes to the WAM. It is important to note that it is the total flow into and out of the arm that is being monitored not power flow to/from the individual joints, otherwise it would be impossible to observe small variations in power flow. Large energy flows between joint motors, which constantly switch roles between motor and electric generator, are uninhibited because they do not affect user safety.

The safety module board has two principal elements, a power conditioning circuit and logic circuit (Figure 2). The latter cleverly utilises a puck, which is identical in every way to the current amplifier pucks attached to each motor even including the encoder head, giving total interchangeability between all pucks. This puck acts as a daughter board and is connected to the main PCB by the male pins mentioned previously.

The safety puck communicates internally to each motor puck and externally to the user's PC via its CANbus. It takes data issued from the motor pucks to calculate end tip and elbow velocities and forces, which are continuously compared with safety levels resident in the puck firmware. If safety levels are being approached or are breached a warning signals or an emergency shut down is issued. The puck also controls the WAM's power-up sequence, always booting into a state in which the bus and the motor phases are separately clamped.

Power flow

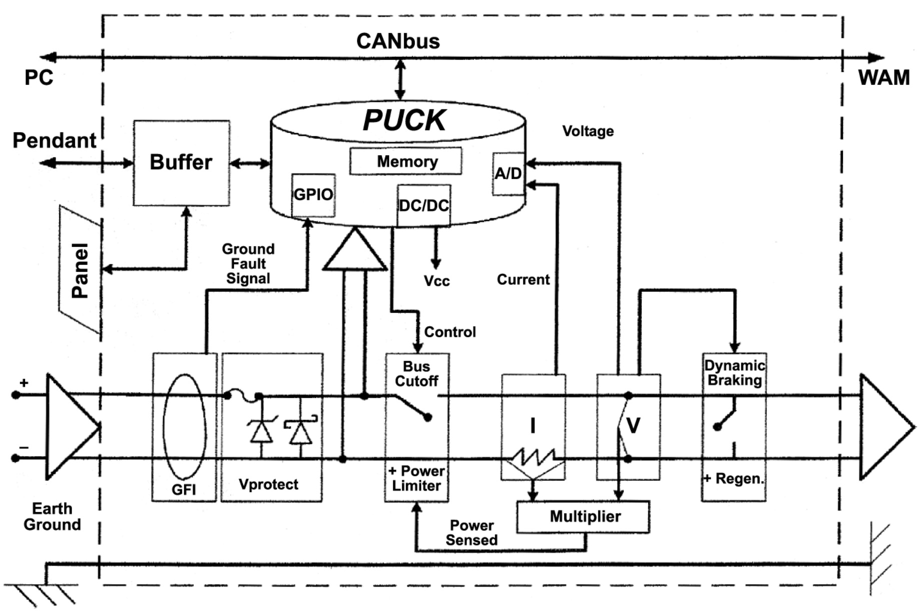
The power conditioning circuit takes the user unconditioned "input" voltage (18-100 V) and "outputs" a number of conditioned logic-level voltages as well as motor bus power – power can also flow in the opposite direction when the arm is being driven by an external human force. Between "input" and "output" are a series of primary and secondary safety-related function blocks, including "ground fault indication" "unidirectional power limiter"; "power calculation" (whose output is fed back to the power limiter block); and "dynamic braking". The latter independently shorts the motor bus and the winding phases for redundancy, creating reverse torques at each joint proportional to velocity and is used when the safety board detects an unsafe condition.

The development of the puck alongside that of the safety board has not only eliminated the external controller and associated heavy cabling of the old WAM but it also saved weight in the arm itself. Now, there are only four power and communication conductors, allowing the designers to reduce the weight of the new WAM by 10 kg to just 25.4 kg while condensing the base to almost one half of the original's volume. The WAM's system weight has been cut from the old design's 105 kg (including controller, cabling and pendants) to just 27 kg for the new arm and wrist (when running native off a DC supply rather than the standard AC/DC converter shipped with a new WAM).

In addition to the major developments on the puck and safety system, Barrett has implemented numerous other significant improvements in the new WAM. One is autotensioning of the drive cables (for which a patent is pending), a process that is completed in two hours and may be scheduled during WAM inactivity. It eliminates the need for tedious manual adjustment and will improve cable longevity because torque is much more precise. Furthermore, the lifetime cable stretch is monitored precisely through the 40,000-count encoder and stored by the local puck to spot a cable that should be replaced during the next scheduled maintenance.

Other advances over the old arm include: smaller footprint; improved software, including haptic capabilities; better wall and ceiling mounting; ten-fold increase in precision; faster responsiveness; and much higher reliability.

Figure 2 Safety circuit schematic



Industrial Robot: An International Journal
Volume 33 · Number 2 · 2006 · 125–130

Mobile platform

The system weight reduction and the very low power consumption are particularly important for mobile platform applications. Recently, Barrett demonstrated a WAM mounted on a cart being pulled around an exhibition powered purely by five 9 V standard batteries. The WAM was actively gravity compensated for intelligent people interaction with the calculations accomplished on just one of the puck DSPs. Further developments in the pipeline to aid mobile applications include ethernet connectivity between arm and PC, on-board wireless ethernet and fuel cell power supply. Since a PC burns more watts than a WAM, Barrett will begin migrating more and more of the intelligence now on an external PC into some of the puck DSPs, using them collectively like a transputer.

These new features on top of the WAM's existing features developed by Barrett are important to the advancement of mobile robotics. Barrett is not a systems integrator and WAM application development is the role of its partners and customers, to whom units of the new robot are now being shipped for beta-testing. For mobile robot platform developments, two 4-dof WAM's have been delivered to MIT for work related to a future programme on robotic planetary exploration (Plate 6).

Other beta-test customers include University of Alberta, Boeing, University of Tennessee for developments in telerobotics, Carnegie Mellon University (CMU) Robotics Institute and the Rehabilitation Institute of Chicago. The latter two organisations are involved in rehabilitation research. The experts at CMU, Yoky Matsuoka and Sam Clanton, have developed software that defines force fields, damping fields and slippery haptic walls within the WAM's control hierarchy. These fields help guide the patient in physical exercises designed to strengthen recovering muscles.

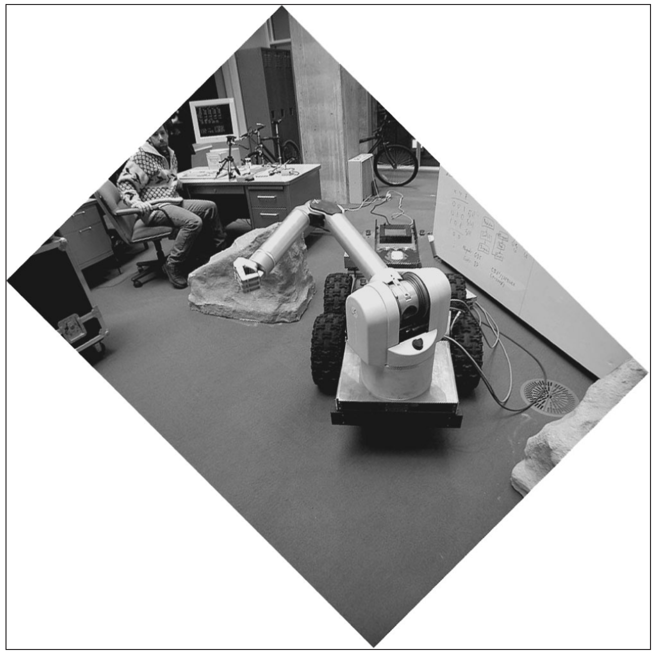
Haptic joint surgery

This ability to define and apply haptic boundaries also has been a major step forward in applying robotics in the operating theatre. The expert here is Z-KAT Inc., based in Florida, a company that focuses on human-interactive robotics in orthopaedic and neurological surgery (Abovitz, 2001). In 2004 Z-KAT formed Mako Surgical to concentrate solely on haptic joint surgery robotics in which WAM technology, for which the company has a licence from Barrett, plays an important role.

The WAM technology used by Mako is a specialised version of the Barrett WAM arm as Rony Abovitz, Chief Technical Officer at Mako Surgical, explains:

> Although it looks very similar to the original WAM some 95 per cent of it has been redesigned specifically for our surgical requirements. It is a more passive device with a higher accuracy and enhanced safety to meet FDA and international medical regulations.

Plate 6 WAM arm mounted on Mars Rover



It uses the same cable-and-cylinder drives with the good backdrivability that enables Mako's researchers to exploit its haptic capabilities. They have developed software that defines haptic boundaries that the surgeon in concert with the WAM feels when sculpting 3D cavities for implants such as knee joint replacements. Further, Mako is able to define haptic guideways that allow the surgeon to access the joint with minimum invasive surgery.

The development of robotics to aid surgery safely and effectively is an indication of how far the technology has evolved from those first pioneering days of the Unimate. It is proof that humans and robots can work together in harmony.

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