

Redefining Robotics for the New Millenium

James Trevelyan

Department of Mechanical and Materials Engineering,
The University of Western Australia,
Nedlands 6907,
Western Australia

E-mail: james@mech.uwa.edu.au

Abstract *The paper argues that the term 'robotics' needs to be redefined as 'the science of extending human motor capabilities with machines' and uses the author's experience with robotics over the last 25 years to support this argument. The current definition is tied by default to the term 'robot' which emerged from science fiction — this tie needs to be broken if robotics research is to be based on reality. The paper reviews the author's research on sheep shearing, vision, calibration, telerobotics and landmine clearance and draws some conclusions which point to the need for changing the contemporary view of robotics. A brief survey of subjects addressed by robotics research journal articles and comments from other robotics researchers support this view. Finally, at a time when many people regard technology, and particularly automation, with considerable skepticism, the proposed definition is easier for ordinary people to understand and support, and it provides more freedom for researchers to find creative approaches.*

1. Defining Robotics

Robotics has been a Cinderella science since it first appeared as a discipline in the late 1970's when mechanical and control engineers first glimpsed the elusive princess: artificial intelligence. Twenty years on robotics researchers are still searching for the foot which matches the glass slipper. In the next century and millenium all this will mostly be forgotten, and the few who bother to investigate the history will wonder how we could have thought what we did.

Recently a passer-by asked a group of robotics researchers "what are you people trying to achieve?" They were waiting for a bus to take them back to their hotels after a conference banquet cruise on Sydney harbour. The response was remarkable: the researchers were lost for words, even though many had taken various drinks which significantly eased their usual inhibitions on speaking out of turn.

Robotics research is in trouble. The era of 'intelligent machines' proclaimed three decades ago has not materialized, and robotics researchers are anxiously looking behind and around themselves, worried that robots are not becoming the ubiquitous machines some people thought they might become by now. We do not know how to make the 'intelligence' and the machines may need to become more reliable and powerful to achieve the independence needed for full autonomy.

At the 1997 conference on Field and Service Robots held in Canberra Hugh Durrant-Whyte commented "In the past 15 years remarkably little progress has been achieved by the robotics research community....we end up developing systems in which the original theory, techniques and technology are often too fragile, too expensive and inappropriate for industrially-hard application".

I have made similar comments to my students for the last 10 years, posing the question "Where are all the robots which forecasts predicted 20 years ago? Why are there so (relatively) few robots being used?"

As robotics researchers look back on the last two decades, it is often difficult to see where the results of their work have led to. Funding agencies have had similar reservations, except perhaps in Japan where the government has embarked on a seven year programme to develop "humanoid robots".

While few of the innovations which emerge from our work ever appear in the form of robots, or even parts of robots, our results are widely applied in industrial machines which we choose not to

define as robots: a common example is the use of computer vision for industrial measurement and inspection. We often find that our robotics research leads not to robots, but better tools which extend the abilities of human workers to the point where they surpass the performance of our robots! This makes it difficult for researchers and other people to understand and appreciate the very significant contributions which emerge from our work.

As we face the 21st century and the next millennium, it is a good time to reflect on this and ask if a change is needed.

A mature view of robotics research would describe it as an intrinsically difficult discipline which yields some very useful technologies. Like particle physicists who seek to explain the fundamentals of our universe, many robotics researchers, at their deepest level, seek to understand and reproduce ourselves in the form of machines. Just as particle physics has stimulated technologies in its search for the very small, robotics has also stimulated technologies in the quest to reproduce ourselves. The world wide web emerged from CERN - the European particle accelerator laboratory, and computer imaging technology has been driven by the quest to reproduce human vision.

While there are obvious similarities, there are also obvious differences. First, particle physics has been arguably more successful in obtaining public research funding. Second, particle physics is based on science, whereas robotics is based on the science fiction play Rossum's Universal Robots (or R.U.R.) from which the English word 'robot' is defined.

1) A mechanical self-controlling apparatus designed to carry out a specific task, normally performed by a human; 2) a person who behaves in a mechanical way; automaton; first used in the play R.U.R. by Karel Capek (1890-1938), Czech dramatist and novelist; apparently backformation from Czech *robotník* serf. (Macquarie 1991)

(1) A mechanical device operating automatically, in a seemingly human way (2) a person behaving like a robot: Czech: *rabu* servant. (Webster 1995)

'Robotics' is then based on these:

1) The theory, design, manufacture and operation of robots and automatic processes, especially in industry; 2) robotic mechanisms (Macquarie 1991)

1) The science or technology of robots, their design, use, etc. (Webster 1995)

Cambridge (1994) still relies on science fiction with the term 'android':

(cybernetics) Application of automatic machines (robots) to perform tasks traditionally done by humans; if the robots are in human form they are called *androids*.

Cybernetics:

The study of control systems that exhibit characteristics similar to those of animal or human behaviour. (Cambridge 1994)

In robotics research, we usually consider a machine to be a robot if it is one of the following:

a) A general purpose, re-programmable, manipulator arm consisting of three or more links and actuators, in series or parallel, with a tool or end-effector at the extremity with either automatic control or manual control from a remote location by a non-mechanical communication link.

b) A mobile platform which functions with a high degree of autonomy using wheels, legs, wings or other means of locomotion.

c) A combination of a) and b).

d) A humanoid robot is anthropomorphic, at least in outline and approximate size, with two legs, two arms, a head with vision, and a torso connecting them.

The demarcation difficulties are recognised in another view:

A surprisingly animate machine (attributed to Prof. M. Brady 1990)

There has been a clear intellectual distinction between the different forms of robot listed above and 'fixed automation' which is machinery which has been purpose-designed for a specific process. Many papers have addressed this issue, looking in particular at the adoption of 'robots' in various industries. By the 1990's the distinction was less clear because 'fixed automation' was becoming more general-purpose and re-programmable, even incorporating manipulator arms and mobile platforms. Robots were often seen as 'less flexible' components of a manufacturing process, and in practice were often purchased and programmed to perform just a single task for their entire working lives. Robot manufacturing companies transformed their names: for example ASEA Robotics became ABB Flexible Automation soon after the merger between ASEA and Brown Boveri.

The difficulty with definitions has become important because 'flexible automation' has adopted many of the results of robotics research, both by adopting technology which emerged from research laboratories and by avoiding many of the problems, such as robotic force control, which research has shown to be difficult. The current definitions of 'robot' and 'robotics' tend to obscure the value of much of robotics research. This affects both researchers and, importantly, funding agencies who now have difficulties providing substantial funding for 'robotics' because of the perceived lack of fruitful results from 'robotics research'.

Even within robotics research, the autonomy associated with the definition of 'robot' is often unwanted, particularly in telerobotics, rehabilitation robotics, human prostheses, and robot-assisted surgery, all of which occupy the minds of robotics researchers. The robot vehicles built by many robotics researchers may not feature any re-programmability or even manipulators.

All this points to the need to redefine robotics on the basis of known science to provide a firm foundation for research in the coming century and millennium. The paper draws on the author's contributions and comments from other researchers to suggest a new definition which could lead our robotics research community out of our current difficulties.

2. Some Contributions to Robotics

2.1. Shearing Sheep

I stumbled into robotics by accident.

In 1976 I was amazed to learn how much Australian wool growers were prepared to pay to develop a machine to shear sheep automatically. A US\$2,000,000,000 industry was driven to near desperation by a shearing labour cost increase of almost 100% in 18 months. They had commissioned two separate research teams to build competing prototypes.

In 1974, David Henshaw, a physicist working in a government textile research laboratory, had discovered that the position of a shearing handpiece could be controlled by measuring the electrical conductivity between the steel shearing comb and the mouth of a sheep. Using a primitive device (figure 1) he had been able to shear a single 'blow' along the backbone of a sheep strapped to a trolley on wheels. Normal Lewis, an engineer-turned-woolgrower, had devised a mechanical solution: two thin sensing wheels could measure the profile of the sheep ahead of a cutter which followed the path they traced out. A private company was commissioned to develop a series of prototypes in Britain. When, by chance, I was asked to evaluate both of these in January 1977, I was surprised that neither group had thought to use computer control: both used hard-wired electronic controllers. Remarkably, they both worked but the mechanical sensing wheels were outclassed by Henshaw's electronic sensing. I observed that computer control would lead to much greater flexibility and would allow the adaptive control needed for high speed operation.

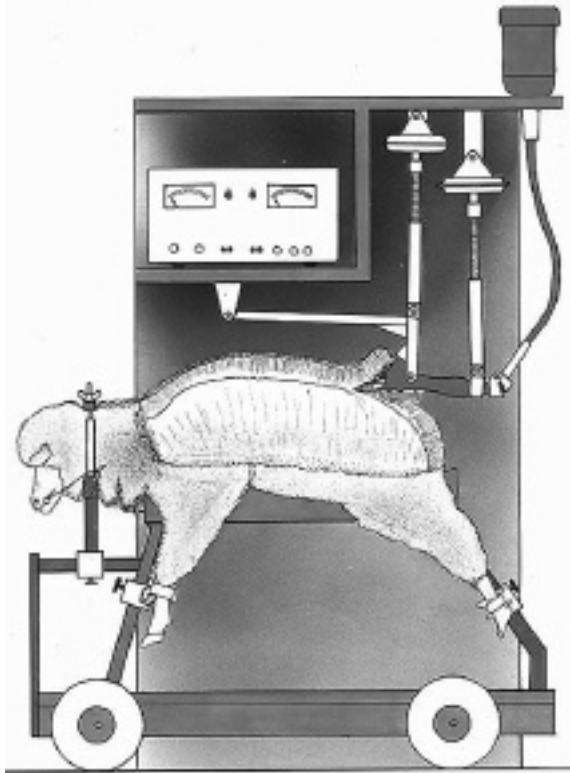


Figure 1. First automated shearing experiment by Henshaw in 1974. Cutter position was controlled by measuring conductivity between comb and skin (through mouth electrode). Simple contact sensor under back of cutter controlled pitch angle. Actuators were lead screws driven by windscreen-wiper motors.

I was surprised that so much of my background in mechanics, machine design, computing, geometry, graphics and navigation came together. With a colleague we designed a seven-axis hydraulically articulated arm with a three axis virtual centre wrist mechanism (figure 2) from first principles¹. A fast (30Hz bandwidth) servo-controlled follower kept the comb pressing gently on the skin in response to comb-skin conductivity measurements and capacitive distance sensors under the comb, compensating for errors in the slower arm movements (4 Hz bandwidth).

¹ See Trevelyan (1992) for details of the research from 1974 till 1990.

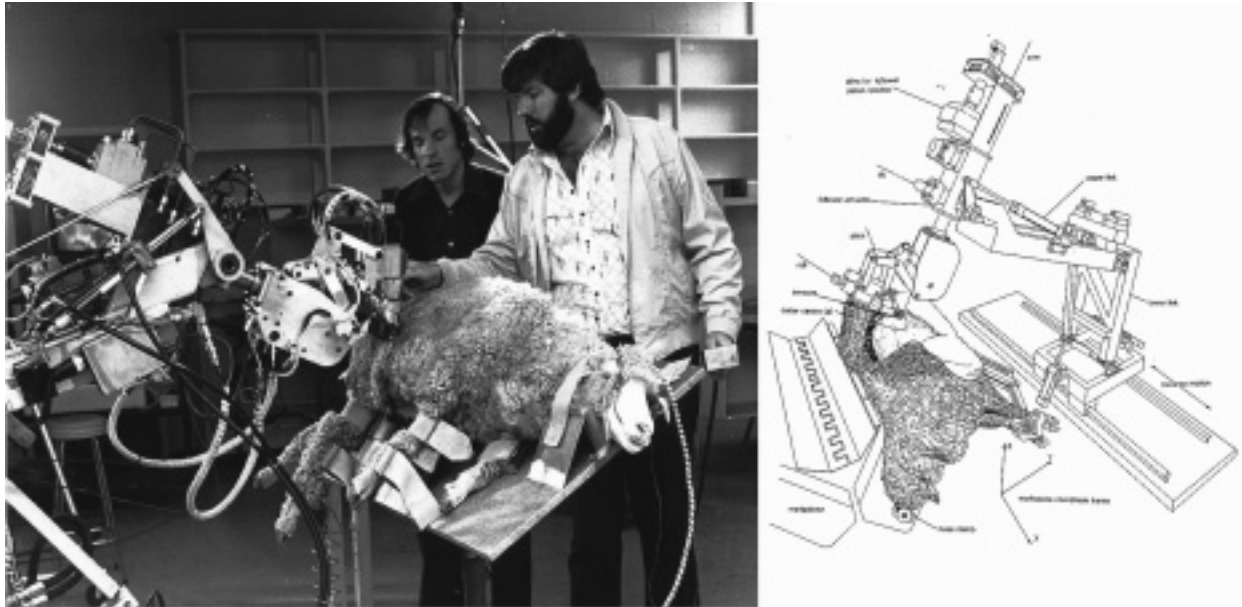


Figure 2. ORACLE robot shearing, watched by author (left) and R. Leslie (1980).

In July 1979, just over 20 months after we started, our machine was shearing wool from live sheep and we reproduced and quickly exceeded the results from the earlier machines. A software sheep was an important element of the control technique: this was a geometric model of the predicted shape of the sheep's body with the wool removed.

Soon after media organisations began take an interest in our work some people suggested we had built a "robot shearer", though it hadn't occurred to me that we had built a robot. We had taken some interest in the "Unimate" at an early stage but the mechanical and control system design was far too clumsy for shearing. We had built a special-purpose machine for shearing sheep, not a general purpose manipulator. However, this distinction was lost when we presented our first film to an international robotics conference (Trevelyan *et al* 1982). The audience laughed and chuckled at first as they saw a sheep lifted onto a cradle and strapped in. However, as our large and seemingly clumsy manipulator quickly and gently sheared the wool almost perfectly there was a deep silence. From then on we were developing a shearing robot.

Once robot shearing had been demonstrated, the wool industry was anxious to see the sheep handling automated as well. Our first 'robot' was only designed for shearing experiments: it's usable workspace was much smaller than its size suggests. We suggested that a new robot design was needed first. This advice was not taken and we were left with the job of designing a complex machine to manipulate a sheep automatically into about 15 different shearing positions, stretch the neck and legs, and hold the sheep still for minutes at a time. Cost was not a major concern: our team grew from 5 to 18 people.

The first sheep manipulator, ARAMP, created by the team in 1983 had 43 actuated movements, most of which could potentially collide with others (figure 3). The mechanical design effort was led by David Elford who had designed much of the world's high speed machinery for peeling, coring and processing fruit in the 1960's and 1970's.

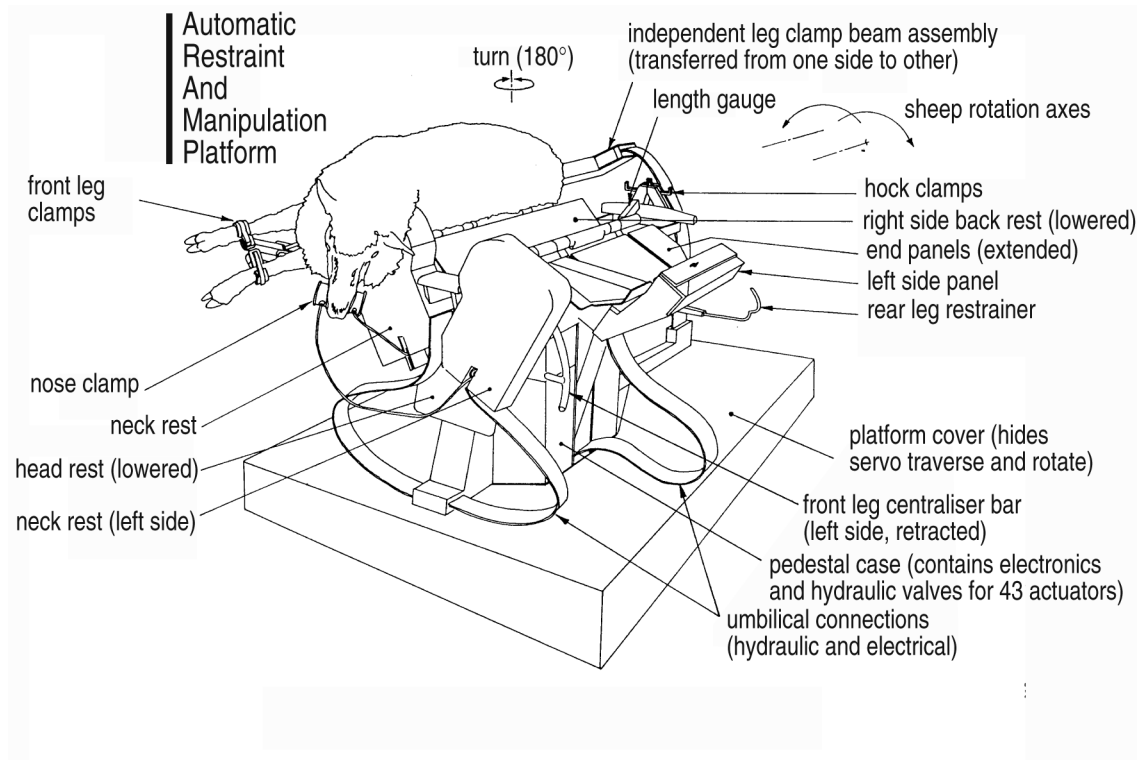


Figure 3. ARAMP manipulator (1983)

A series of successful demonstrations in 1983 led to funding for a new shearing robot with a large workspace. We were now forced to confront the singularity problems which ORACLE, our first robot, neatly side-stepped. Analytical techniques had been developed to guide robot trajectories away from singularities. However, these methods could not cope with the requirement for on-line trajectory adaptation needed for shearing sheep unless we declared large 'zones' around singularities which had to be avoided, just as known physical obstacles had to be avoided (Kovesi 1985). Fortunately we managed to design a robust singularity-free wrist mechanism (Trevelyan *et al* 1986) which removed many of the otherwise challenging design constraints on the new SM (Shear Magic) robot and its control software.



Figure 4. SM Robot and SLAMP manipulator. Photograph shows a shearing demonstration in 1989.

The SM robot greatly impressed woolgrowers with its simple appearance (figure 4). This was no accident: we had hidden the complexity which ORACLE and ARAMP had displayed on their exteriors by incorporating all the hydraulic piping and electronics inside the structure. In commercial practice this would have been a fatal error, greatly increasing manufacturing and maintenance costs, but it was vital at that stage of the project.

The fourth and final mechanical stage of development was to simplify sheep manipulation, but simply hiding the complexity was not acceptable. Sheep loading, which had been ignored in designing ARAMP, had to be taken seriously. The head had to be manipulated accurately as well to shear around the eyes and ears. Most robotics research stops are three or so simultaneous arm manipulations: a sheep has four limbs and a head joined with a flexible neck and trunk. We had to keep all five 'extremities' under precise mechanical control while simultaneously turning the sheep. There were no easy answers.

For 18 months we worked towards solutions which we knew in our hearts would be impractical. Fortunately, further simplicity emerged from this crisis in confidence and we named this creation 'Simplified Loading and Manipulation Platform' or SLAMP (Trevelyan and Elford 1988). In February 1989, almost ten years from the first robot shearing, we demonstrated automatic loading and shearing of the entire sheep. It took 25 minutes so the final research effort was directed at reliability and shearing time, though only a few of the results were integrated into fully working demonstrations.

One of the most important changes was to abandon our original dependence on measuring conductivity between the comb and the skin. This is almost directly equivalent to the problem of force control which is well-known to robotics researchers. Skin conductivity was directly related to contact force, but the characteristics varied wildly and many other effects had to be accounted for.

We devised a completely different approach though (fortunately) no significant mechanical changes were needed. We used hydraulic pressure to apply a known force to the shearing comb (subject to friction uncertainties) and measured the resulting comb displacement. The results were startling. Before this, the fastest usable shearing speed was about 10 cm per second and less on many parts of the sheep. With our new technique we could run the comb over shorn skin at 80 cm per second, though the cutter never had enough power to shear wool at this speed, and the robot's hydraulic supply had difficulties keeping up the pace. More importantly we could reduce the bandwidth needed for the robot arm from the 25 Hz specification for SM to about 5 Hz. This represented a major cost reduction for future shearing robots.

Another vital development was in machine vision. We found that none of the established techniques in computer vision helped overcome reliability problems in measuring images of sheep. This was a key step in predicting an accurate 'software sheep' for every animal. We evolved our own variant of 'snakes' or adaptive contour models (Kass 1988) which were so reliable that it was difficult to measure the incidence of failure. (figure 5).

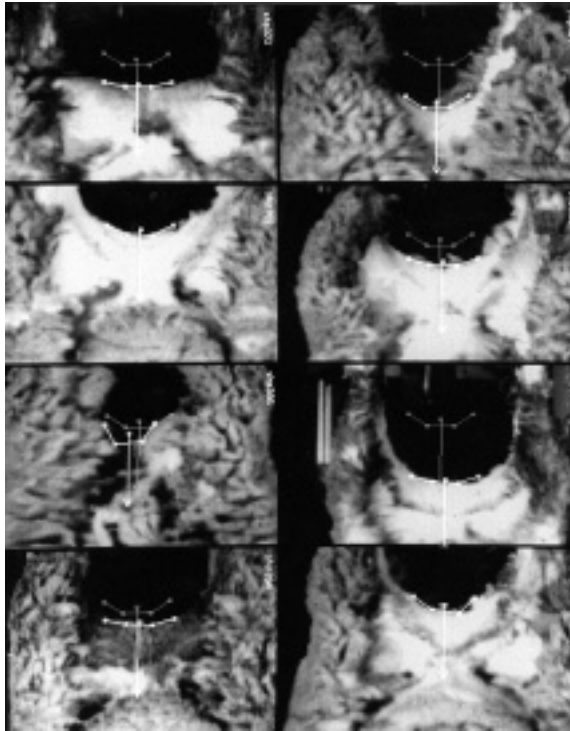


Figure 5. Snakes with pre-formed shapes and simulated mechanical properties locate features in sheep images. Photograph shows crotch areas of 8 very different sheep.

Many people thought our robot was 'intelligent' and our work formed part of the exhibition which accompanied the 1988 IJCAI in Sydney. We showed how we had achieved the smooth flowing movements of human shearers with an elegant means of dealing with interruptions needed to push wool out of the way or avoiding the occasional skin cut (Trevelyan 1989). However, many delegates were genuinely puzzled when they learned that we used no expert system shell, no artificial neural networks, and wrote all our software in Fortran 77.

The wool industry experienced a financial disaster in 1990 when the three leading wool buying regions withdrew from the market. Russia and Eastern Europe ran out of credit and China was denied credit in the aftermath of events of May 1989 in Beijing. Prices and demand plunged. Other long term research programmes were drastically curtailed. Our research was completed in 1993 when a major financial feasibility study concluded that robot shearing offered excellent prospects. However, efforts to form a commercial joint venture between the wool industry and merchant banks collapsed due to the state of the wool industry at the time. The investment required, about US\$35 million, was small for such a huge industry yet woolgrowers were unwilling or unable to invest in anything except their immediate short-term survival.

Looking back, as a research project, robotic sheep shearing was an outstanding success and there have been two significant outcomes. First we devised a systematic approach for sharpening shearing combs and cutters which has been taught to shearers since 1990. Before, this was regarded as a 'black art' mastered by only a few shearers. Second, the SLAMP technology has been refined and greatly simplified and is now under commercial development to eliminate all the heavy lifting from manual shearing (Trevelyan 1996a). This means that shearing will no longer be the preserve of an elite cadre of physically strong and supple males who only work as shearers for an average of 4 - 5 years. Men and women will be able to develop their skills over a lifetime improving industry performance in many respects, not just shearing time. Shearing robots are still seen as the ultimate long term solution for the 21st century. (Elford 1999)



Figure 6. SLAMP manipulator simplified and refined for manual shearing (1996).

2.2. Simplicity in Robotics

In 1992, for a complete change, I decided to focus on a theme of simplicity in robotics with long-term, low-budget research using an ASEA IRb6 robot and PC computers as building blocks, with minimal internal modifications or specialised hardware. I reasoned that working with a standard robot and PC's would make it easier for students to transfer their technology to industrial partners. Robotics needs reliable low-cost building blocks to build reliable complex systems, and I was interested in working in a completely different direction from the rest of the discipline.

2.3. Calibration and Accuracy

Inspired by ideas from Giovanni Legnani (Legnani et al 1996) I worked on the problem of absolute positioning accuracy since I had observed that there did not seem to be a low cost, simple solution to the problem of industrial robot calibration. Published techniques relied on expensive sensors and were of limited use in practical industrial cells where part and fixture errors are as significant as robot errors. Working gradually with students, we devised an elegant laser and mirror/lens device, which provides highly accurate measurements, and a recursive filter to estimate kinematic parameters. (figure 7, Cleary 1997). This work is not yet completed. The calibration technique works very well in our laboratory but it has not been easy for others to implement. There is a need for this, particularly from research students who often ask for details of our methods.

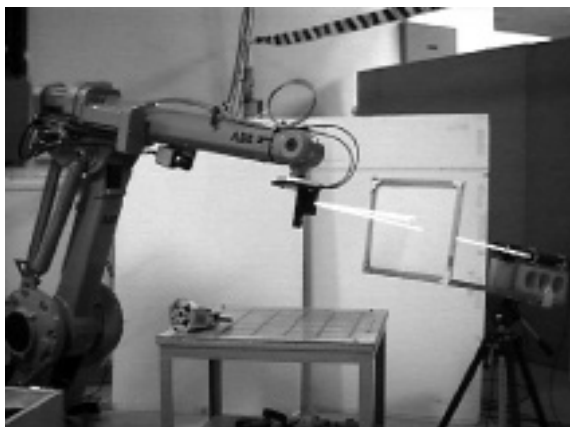


Figure 7. Calibrating the robot with laser beam. The laser beam emerges through a pin hole in the screen and is reflected off a plano-convex lens on the robot gripper mounting. The lens is coated to provide front and back surface reflections. A CCD camera alongside the laser collects images to measure the positions of the reflections on the screen - the spot positions reveal pose errors in the wrist which lead to an improved kinematic model. Repeatable errors were reduced to less than 0.1mm using this technique.

2.4. Vision

With help from a research grant, I continued work on snakes for computer vision in an attempt to extend the successful sheep shearing techniques for use in plant images. (Trevelyan and Murphy

1996). Here I faced a significant obstacle: the software relied heavily on graphical programming which was implemented using a simple home-grown GUI toolkit in X-Windows on a Unix workstation. Transferring this to a PC running DOS was not easy. We developed a low-level X-Windows environment (Little-X) for DOS which seems to have been useful to many people since we placed it on our web site. We finally concluded that Visual Basic provides a useful environment for Windows operating systems, after discovering many gaps in Microsoft documentation. With the recent emergence of reliable Linux implementations, one might think that all the time invested on Microsoft operating systems was wasted effort. Without this, however, we would not have been able to proceed to another outstandingly successful project - web telerobotics.

2.5. Web Telerobotics

I challenged an outstanding new PhD student, Ken Taylor, to work on a new question: "where are all the robots?". Why had the optimistic forecasts of the late 1970's and early 1980's been so wrong? At that time, many had forecast that robots and automation would completely displace manual labour from manufacturing by the mid 1990's and by 1994 it was clear they were very wrong. Was there any prospect for future growth in robotics? Is there a missing technological element which has prevented this growth? Ken found this was a difficult question so he diverted himself by exploring the internet which had just been transformed by the World Wide Web. A web page image of a coffee pot at Cambridge University, which was updated each time a user requested it, inspired him to realise that any web user could control our robot if they could obtain pictures of it in the same way. As quickly as possible he mobilised other students with my research staff and our ASEA robot went on-line in September, just 3 weeks after Ken Goldberg's group in Southern California went live with their two axis "Raiders" telerobot. Users could use the robot to manipulate a set of childrens' building blocks and several remarkable structures have been created (figure 8).

Ken Taylor was also inspired by the concept of geographically separating thinking and action. In conventional robotics, designers often find that the number of states an automatic system can enter greatly exceeds their capability to program appropriate responses. Human minds are potentially available in great numbers, greater than the need for manual labour alone. Low cost internet telerobotics offers the chance to use this potential, centralising machinery, but with a dispersed thinking work force.

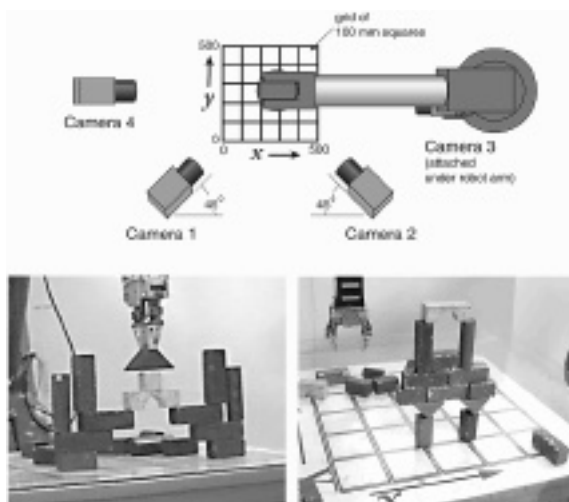


Figure 8. UWA Telerobot (plan view above) has attracted about 250,000 users since going on-line in 1994. Users see images of the robot from up to 4 cameras in different positions around the work space. A few create surprisingly complex structures, while most just move the robot----- fig

Ken and his colleagues struggled with unreliable operating systems, web servers and web browsers, but by the middle of 1995 were reliably collecting data on the actions of the thousands of visitors to the telerobot web site each month. The most surprising result of the telerobot project has been the consistently large number of visitors who access the site, year after year. This raised the question "why" and we are still working on issues arising from this.

Part of the answer may lie in the intrinsic entertainment value of telerobots, we think they have great potential for recreation. Users often remark on the experience of controlling real machines on the other side of the world in their comments they leave behind. In the future it may be feasible to provide intimate telerobotic access to wildlife reserves where human entry would destroy them.

Barney Dalton joined the group in 1996 and steadily transformed software "hacked" together into a properly structured system which now operates extremely reliably. Short term visitors have also made contributions such as an augmented reality interface which allows users a more intuitive, graphical interface by Harald Friz (Dalton *et al* 1998).

2.6. Demining

In 1994 and 1995 several people suggested I should design a robot to remove anti-personnel landmines which were being recognised as a major disaster in about 30 countries around the world. I devised several approaches such as a cable-suspended robot (Trevelyan 1996b, Trevelyan 1997), but soon recognised that the absence of reliable sensing would make such a device quite impractical.

Mine clearance, now known as humanitarian demining, is a tedious process because every fragment of metal located with metal detectors needs to be carefully investigated as a potential mine. In some areas thousands of metal fragments are unearthed for every mine removed. When the density of these fragments exceeds 20 or so per square metre, the entire ground surface has to be investigated, centimetre by centimetre. Dogs can help under some circumstances but take time to train and adapt to local conditions and deminers must avoid using them where this is thick vegetation or strong scents from recent human habitation, rubbish or pollution.

Military and other government research programmes have invested hundreds of millions of dollars in the search for better sensors, but the goal remains elusive. What is needed is a "no-mine" detector which will tell a deminer that the ground he is about to walk on is safe. A metal detector cannot distinguish a mine from a metal fragment, so one must rely on other sensors to do this. Many have been tried including ground penetrating radar, infra-red, microwaves, acoustics, even water jets. Unfortunately the signals from these other sensors are highly correlated with metal detector signals so sensor fusion has so far returned disappointing results. By late 1998, detection probabilities in realistic situations were of the order of 90% which is 2 - 3 orders of magnitude short of the 99.6% needed for confidence and safety (Trevelyan 1998).

Mechanical clearance has not been successful either. While some machines have exceeded 90% clearance in trials, verification is difficult after the machine has dispersed metal fragments up to 40 cm below the ground.

After six months of careful research I concluded that robotics technology offered little chance of practical results within the next ten years — an assessment which remains unchanged three years later. However, with almost no systematic research into all the aspects of demining *except for detection* there were many opportunities to contribute practical results within a short time. Deminers were working with primitive tools and little or no protection because imported "western" military equipment was bulky, uncomfortable and expensive. While there was plenty of scope for simple solutions, there were many obstacles and difficulties.

Demining operations usually take place in a "fourth world" where conditions are usually worse than typical third world conditions. Social, commercial and political organisations have usually collapsed: this has either been the cause or consequence of civil wars in which landmines have been an attractive low-cost weapon for harassment and terror. In this environment making any organisation work effectively is a major achievement in itself. Adapting new technology poses particular difficulties because local people have missed out on the education opportunities taken for granted even in most third world countries.

The Afghanistan demining programme is one of the most effective in the world (UN 1998). We established a research group in Pakistan with the help of family connections, staffed entirely with local engineers and technical support staff, to work closely with Afghan deminers. We can access

their ideas and suggestions free of cultural inhibitions such as "we must please the westerner who knows everything". We developed ideas for protective clothing, improved digging tools with blast shields, and body armour in Australia which have been altered and refined with help from deminers working under local conditions (figure 9, Trevelyan 1999). Some of these are now being provided for field use by deminers.



Figure 9. Afghan deminer testing tools and protective clothing watched by engineers from Hameed and Ali Research Centre, Islamabad, Pakistan.

3. Some Personal Conclusions

Rate of technological change

The "ever increasing rate of technological change" is a myth. Technology is changing, but not at the rate of a century ago when electricity and telecommunications spread across the western world in three or four decades. My eldest son completed his degree four years ago, but the *last time* men landed on the moon was two years *before* he was born.

Intelligence

First, many of the actions we associate with intelligent conscious behaviour can be automated, but the actions all people perform unconsciously and take for granted defy comprehension, let alone any serious attempt to imitate them.

Simplicity

Simplicity is the key to successful engineering. To be useful, robots must not only seem to be simple, but they must be intrinsically simple as well.

Force control

It is much simpler and more effective to provide effective force control by regulating a force generator, rather than by controlling the relative position of objects and relying on erratic and sometimes obscure surface interactions to produce a desired contact force.

Advances in the field

The most interesting advances in robotics emerge from new applications where a given level of performance is required for success. The sheep shearing robot provides a compelling case for this. I think that we would never have embarked on the research if we had been immersed in robotics research at the time we started: we would have dismissed the project as being beyond the state of the art. At the time we were conducting our first shearing tests I found that robotics researchers using computers several times more powerful than ours just for controlling a manipulator arm. Our smaller computer handled this with perhaps 1% of the effort because it also had to provide skin sensing, compliant force control, surface modelling and adaptation, on-line trajectory modification, fault monitoring and safety interlocks. To do this we had to develop original methods for manipulator control which are still not well appreciated in robotics. We developed these techniques because we started with a set of performance requirements and we designed our robot and control system from basic principles to meet those requirements, rather than adapting current research results in robotics.

Technology Transfer

Robotics technology usually has to be transferred by moving people. It cannot easily be communicated in written form, software or even working hardware. When, at the conclusion of the sheep shearing project, the wool industry stored all our working drawings, computer software, even the sheep shearing robot itself, to secure "intellectual property" they had a complete definition of how we would *not* build a future sheep shearing robot! We took that knowledge with us, but the potential is still to be realised, of course.

4. Evidence from the Field

Robotics is a research discipline which appeared quite suddenly in the early 1980's, almost 10 years after international conferences on robots began (such as International Symposia on Industrial Robots). Several leading journals commenced within months of each other, and it is instructive to examine the contents of these journals then and now.

Topics from randomly selected early issues of the International Journal of Robotics Research (3:3), International Journal of Robotic Systems (2:4), Robotica (1: p189-) include the following:

- *Dynamics and control of flexible arm robots
- *Dynamics and control of rigid manipulators
- *Manipulator kinematics, efficient calculation techniques
- *Motion planning, off-line programming
- *Object recognition from vision, range data and tactile sensing
- *Studies on actuators, transducers and transmissions
- Accuracy improvement for rigid manipulators
- Image processing for vision
- Robot applications, future research
- Telerobotics

Recent issues of International Journal of Robotics Research (17:12), International Journal of Robotic Systems (16:1), Robotica (16:6) included the following:

- *Dynamics and control of flexible arm robots
- *Dynamics and control of rigid manipulators
- *Manipulator kinematics, efficient calculation techniques
- *Motion planning, off-line programming
- *Object recognition from vision, range data and tactile sensing
- *Studies on actuators, transducers and transmissions
- Kinematics of assembly tasks, automatic fixture design
- Mobile manipulator and platform control
- Mobile robot map-building with sonar

Optimization of robot design parameters Walking, hopping robots

The non-common topics of the recent issues are not new of course. Mobile robots emerged in the 1950's and 1960's, assembly tasks have been researched since the 1970's, and walking robots since the 1980's.

This brief analysis might confirm what many researchers have suggested: that research in robotics has, to a degree, stagnated. According to this view, observable progress results more from developments in enabling technologies, such as computing, than from any intrinsic advances in robotics itself.

An alternative interpretation is that robotics was a mature field for research before these journals became established, and the gradual progress reflects a longer history than these journals would suggest. There has been observable progress: there are many more tools available to build robot hardware and software. Robotics research is often applied in industries without reference to any researchers or even publicity. Examples of entirely indigenous robotics technology which I know of in Western Australian companies² include:

- elegantly simple underwater ROV's
- large-scale de-scaling telerobots for process plant storage tanks
- deep sea oil and gas pipe-laying machine
- sterilizable abattoir robot
- abattoir automation systems and automatic meat inspection and grading technology
- target robots for counter-terrorism practice range, and
- on-line measurement of ore properties using robots

As researchers, we tend to exclude some of these from our definition of 'robot' but we only detract from our own work by doing this.

4.1. Comments from Researchers

While writing this paper, I sought comments and ideas on directions for robotics research in the new millennium from many people with different backgrounds. Their responses helped to develop the argument which this paper proposes. I have reproduced an edited selection of comments.

Robotics researchers provided the greatest number of responses:

"[Robots] are designed with the usual objectives of replacing labour but what will their real applications be in the future?" "One should not need not be a robot engineer or scientist to use robots or use robots to create new applications." (Ang)

"I have a moderately futuristic vision of human-wearable robots that act as extensions to the human body and help the user accomplish tasks he or she might otherwise not be able to. Our immediate work focuses on aids for children with disabilities." (Kumar)

"Robotic implants for humans. We already have intelligent prosthetic hands. No doubt there will be other areas for using intelligence inside replacement modules." "I think more work is needed on actuators: too much of the effort concentrates on intelligence".... "a robotic factory on the moon will prepare a base for humans to inhabit" (Daniel)

"Robots should be modular, built from standard, fully integrated components" "Too many papers address hypothetical, foolish problems with unrealistic constraints: this is counter-productive to the advancement of the field" "There is not enough work on new actuation methods". (Goldenberg)

² Western Australia has a population of only 1.7 million. Its industrial base consists largely of agriculture, mining and offshore oil and gas industries.

"What is a robot, really?" ... "some of these people are fitting computers and lasers to a road grader but they should redesign the grader instead" ... "When is a robot not a robot?" (Phillips)

Students:

"I doubt that robots will be used much for applications where the environment is constantly changing" (Radzivanas)

"The internet will affect robotics" ... "with tools like MATLAB and LabView, independent of the hardware and operating system, I can now write the software I need for the arms I design" (Ratner)

Industry:

"...the treatment of human factors in process automation systems is at best poor and sometimes insanely bad. The integration of people and machines is difficult and challenging" ... "we need an alliance between engineers, human factors experts, philosophers, sociologists, even shrinks who run rats through mazes." (Varley)

The comments from researchers help to confirm that they (among others) have broadened robotics research well beyond the current boundaries. Some informal comments also reveal frustrations which reflect the contradictions of the existing definitions. However, there are clear long-term visions which promise a long and productive future for robotics research.

5. Conclusion: Applications and Definitions

It is paradoxical that much of what we research is applied in machines we choose not to define as robots. Indeed, it is only our definition which limits the number of robots in use because the technologies which extend or supplant human labour are the same we use to build the robots in our research laboratories. Two examples will suffice: many robotics researchers would not include these as robots.

A "Kreepy Krawly" pool cleaning machine performs a task comparable to what many "intelligent floor-cleaning" robots are built for and satisfies the Macquarie definition of 'robot'. It avoids obstacles by deflecting itself away from them. It incorporates simple mechanical guidance steer it downwards if it climbs to the water surface, and accomplishes its task by random motion which eventually cleans the entire pool surface. Yet many would not call it a robot because it does not use a computer and cannot be programmed (though it does not need to be programmed).

A cruise missile incorporates many of the navigation and control techniques explored in the context of mobile robotics research, but we may feel uncomfortable accepting a potentially harmful weapon as a robot.

We create these unnecessary difficulties by retaining inappropriate definitions.

The technologies we use to build robots have been, and are being applied extensively in almost every industrial activity in the world. The research we perform improves these technologies by imposing new demands and extending the known limits of performance and programming. Our students of robotics learn about automatic control systems, real time software, communications, actuators, mechanisms and sensors and are then employed to build machines and process plant for mining, manufacturing, warfare, transport and power generation. They make selective use of robot technologies when needed and, on rare occasions, actually build new machines which we researchers accept as being robots, or at least 'robotic'. They learn that the vision of total and complete automation that inspires much of our research is neither practical nor appropriate because it usually costs more than simpler solutions to the ultimate problem which is to make the best use of available resources.

Redefining robotics will not make much difference to the way technology develops. However, there is an urgent requirement to redefine what we, as robotics researchers, are trying to do to avoid the inherent contradictions which our present definitions lead to. It will also help our research students develop a broader and more mature approach to the discipline.

Robotics researchers have traditionally drawn on many more specialized or fundamental disciplines. These include:

- Mechanism theory
- Mechanics, dynamics
- Mechanical design
- Materials
- Hydraulics
- Mechatronics
- Computer science and software engineering
- Computer vision
- Electronics and electrical engineering
- Communications
- Sensors, transducers
- Optics, acoustics, radar
- Automatic control, cybernetics
- Biology, zoology
- Human physiology and psychology

It is this wide spectrum of contributing disciplines which makes the robotics the challenging and stimulating discipline it has been.

The current definitions focus on the core notion of automatons though they originate more in the science fiction writings of this century than reality. This conflicts with what we have learned: complete automation is often infeasible, impossible or simply unwanted.

5.1. Robotics: the science of extending human motor capabilities with machines

The definition I have proposed encompasses the full range of our research activities, but does not lead to contradictions in applications. Almost all robotics research is motivated by the desire to extend human capabilities, whether by substituting an automaton for the human, or by incremental means which increase existing human capabilities.

One might argue that the proposed definition fails because it is too broad: all machines extend human capabilities in some way whether they write more legibly (computer printers) or transport us (cars, carts, or bicycles). However, robotics has created a coherent framework from which designs for useful machines emerge. The evidence for this is all around us in the successful application of robotics-related technologies. The essential starting point is an existing human activity which takes effort, or carries a risk of injury, or a desired activity which humans cannot perform. Some would be tempted to qualify 'machines' with the word 'intelligent'. However, this would exclude 'dumb' or 'simple' machines which are often more effective than the 'intelligent' machines which have been tested so far.

A major practical difficulty faced by young researchers is the volume of literature. The robotics discipline alone produces several thousand papers a year in conferences and journals. The contributing disciplines contribute tens of thousands more. Even within robotics, it is not difficult to find prominent research papers which do not mention almost identical work being published by other groups working on similar problems. The traditional academic approach is to narrow the scope of a student's research to reduce the need to read supporting literature. One might, for example, suggest working exclusively on manipulator arms with 5 rotary and 3 prismatic joints.

Given this difficulty, I would argue that the proposed definition of robotics provides an enlightening starting point, namely the study of human skill or capability for a particular activity. We pursued two major research efforts this way: sheep shearing and mine clearance. It was essential to study the human activity closely, not just at the beginning of the project, but all the way through. In the case of shearing, we improved our understanding by trying to mechanize it: when the robot failed to perform as expected the cause was often an unsatisfactory understanding of the human skill. The telerobotics research emerged from a question: "Where are all the robots?" This, in turn, eventually provoked this paper which answers the question by redefining robotics.

I should not finish the paper without briefly considering the consequences for the definition of a 'robot'. In essence, I would argue that the relationship between my definition of 'robotics' and 'robot' is not unlike that between musicology³ and music. Expanding the definition of 'robotics' need not affect anyone's interpretation of the word 'robot'.

What, then, are the implications of changing the definition of 'robotics' on the way we conduct our research?

First, we need to address a significant short-coming: we need to give much more consideration to the ways in which people interact with machines. Just as the field of 'human-computer interaction' has become critical for computing, we need to embrace the well-established disciplines of ergonomics and human factors within robotics research. We need to invite specialists in these disciplines to conferences to stimulate more awareness of these issues.

Second, we need to take time to examine case studies of successful technologies which we have not, until now, considered to be robotics. We need to understand different approaches and how these advances were made.

Third, we need to address the problem of access to proliferating scientific literature, particularly for students. This is not a problem which is unique to robotics. However, given the number and depth of supporting disciplines, the volume of potentially relevant literature is immense. The internet has helped to some extent, but it has not prevented parallel teams working on the same problem, unaware of each other, even in the same country.

Fourth, we need to work more closely with biologists, zoologists, and human physiologists and psychologists in attempts to replicate aspects of humans or animals to better understand human capabilities and mechanical limitations.

Finally we need to recognize the achievements of robotics research we have chosen to ignore by adopting a fictional definition.

In the words of the introduction, we need to postpone the search for the foot which fits the glass slipper and make some definitions which will provide a secure foundation in science for a new millennium of robotics research.

6. Acknowledgements

The author would like to thank many colleagues who have supported his work in robotics, particularly the sheep shearing project team, and the organisations which have generously supported the research projects: The Woolmark Company (formerly Australian Wool Corporation), Australian Research Council, US Department of Defense and the University of Western Australia. Thanks are also due to Michael Arbib, Michael Kassler, Jamie Kassler, Ron Daniel, Vijay Kumar, Andrew Goldenberg, Marcello Ang, Jack Phillips, Gintaras Radzivanas, Danny Ratner and Bruce Varley for their comments and contributions on this issue, and to Samina Yasmeeen for reviewing the argument and remarking that the sheep shearing robot was a machine: a robot had to have eyes.

³ Musicology: the scholarly or scientific study of music, as in historical research, musical theory, ethnic music, acoustics, musical instrument design and manufacture, hearing, perception, human skills etc. (Macquarie 1991)

7. References

- Cambridge (1994) *The Cambridge Encyclopedia*. Crystal, D. (editor), Cambridge University Press, UK.
- Dalton, B., Friz, H., and Taylor, K. (1998). Augmented reality based object identification in internet robotics. *International Conference on Telerobotics* (details to follow)
- Durrant-Whyte, H. (1997) Realising field robotics applications. *International Conference on Field and Service Robotics*, 8-10 December 1997, Canberra, Australia, pp1-8.
- Elford D. (1999) Personal communication.
- Kass, M., Witkin, A., and Terzopoulos, D. (1988). Snakes: active contour models. *International Journal of Computer Vision*, 1, pp. 321-31.
- Kovesi, P. D. (1985). Obstacle avoidance. *2nd International Conference on Advanced Robotics (ICAR)*, pp. 51-58, Tokyo.
- Legnani, G., Mina, C., Trevelyan, J. P. (1996). Static calibration of industrial manipulators: design of an optical instrumentation and application to SCARA robots. *Journal of Robotic Systems*, Vol 13, No. 7, pp 445-460.
- Macquarie (1991). *The Macquarie Dictionary*, 2nd Edition, A Delbridge (editor), Macquarie University, Sydney.
- Trevelyan, J. P. (1989). Sensing and control for sheep shearing robots. *IEEE Transactions on Robotics and Automation*, Special issue on sensing and control, 5, (6), pp 716-27.
- Trevelyan, J. P. (1996a) Automating Sheep Shearing. *Service Robot*, Vol 2, No. 3, 1996, pp 27-30 (invited paper).
- Trevelyan, J. P. (1996b) A Suspended Device for Humanitarian Demining. MD96: IEE Conference on Detecting Abandoned Landmines, Edinburgh.
- Trevelyan, J. P. (1997) Robots and Landmines. *Industrial Robot*, Vol 24, No. 2, pp 114-125.
- Trevelyan J. P. (1999) Protecting Deminers. *Proceedings of Austcare Demining Workshop*, Austcare, Sydney - see also World Wide Web: <http://www.mech.uwa.edu.au/jpt/demining/>
- Trevelyan, J. P. and Elford, D. (1988). Sheep handling and manipulation for automated shearing, *International Symposium and Exposition on Robots (19th ISIR)*, pp. 397-416, Sydney.
- Trevelyan, J. P. and Murphy, P. (1996) Fast Vision Measurements using Shaped Snakes. *International Conference on Advanced Robotics and Computer Vision (ICARCV96)*, Singapore 1996.
- Trevelyan, J. P. Key, S. J., and Owens, R. A. (1982). Techniques for surface representation and adaptation in automated shearing. *12th International Symposium on Industrial Robots (ISIR)*, pp. 163-74. Paris.
- Trevelyan, J. P., Kovesi, P., Ong, M., and Elford, D. (1986). A wrist mechanism without singular positions. *International Journal of Robotics Research*, 4, (4), pp. 71-85.
- Webster (1995) *Webster's New World Dictionary*, 1995 edition, Neufeldt, V. (ed), Simon & Schuster, New York.