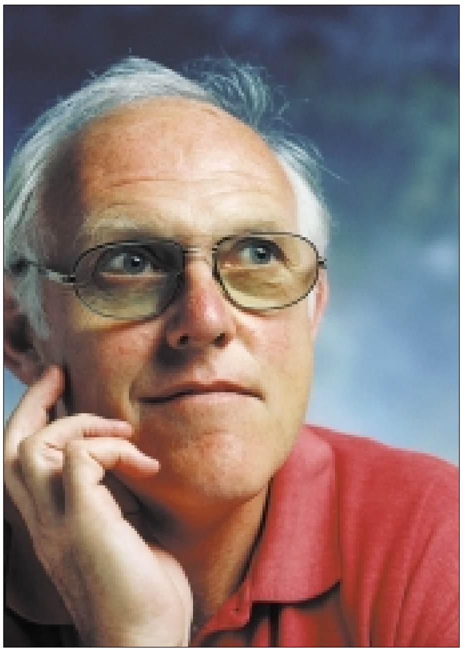
Pure and applied

This year's IEE Faraday Medallist, **Mike Brady**, is using the lessons of his pioneering work in machine vision and robotics to transform the capabilities of medical imaging systems. **Roger Dettmer** traces the common themes in a remarkable career



Discontent is the proper condition of the young. In the laid-back world of late 1960s Australia, life, for Mike Brady and his wife Naomi, has never been better. They've a great bunch of friends, Brady is captain of the Australian National University soccer team, and his PhD project, supervised by the internationally renowned group theory specialist Bernhard Neumann, is going 'pretty well'. But there's a shadow in this, otherwise, sunlit world – he's getting bored with pure mathematics. 'I realised,' he says, in the complaint of academics down the ages, 'that nobody gave a damn about what I was doing.'

Brady had come to pure mathematics almost by default. At school, in Prescot in Lancashire, he'd been 'turned on' by the application of mathematics. Unfortunately, this early enthusiasm did not survive his experience as a student at Manchester. At that time, Neumann, who had been a member of the University's Mathematics department since 1948, was the dominant figure in mathematics at Manchester. Brady was an undergraduate at UMIST, where a number of his teachers had originally been students of Neumann. Inspired by the teaching of pure mathematics, not least by John Shephard, Brady's interest in applied maths began to pale, and he was drawn more and more towards the aesthetic pleasures of group theory. In 1967 Brady moved to Australia to start his PhD under Neumann, then Head of the Mathematics Department at the Institute of Advanced Studies.

But, even as he was writing up his thesis, his natural inclination for the applied rose, irrepressibly, to the surface. 'There must,' he reasoned, 'be something as intriguing as pure mathematics, but which actually addresses real problems.'

Computing looked a promising possibility. Brady had never actually seen a computer; nevertheless, he started reading 'great globs' on the subject and became fascinated by the possibilities of artificial intelligence, especially the prospect of machine perception. 'Wouldn't it be great', he thought, 'to build a machine that could actually see.'

First sight

But how was he to pursue this new-found enthusiasm? He found a copy of the proceedings of a computer conference in the University library, which, helpfully, listed the addresses of all 70 participants. Brady wrote to each one of them asking for a job, and got seven offers: 'I think they were looking for a kind of mathematical hired gun'. There were a few post-doctoral positions, a couple of jobs in industry; then out of the blue he was offered a lectureship in computer science at the University of Essex. In 1970, still not having set eyes on a computer, Brady arrived at Essex to teach, and learn, computer science. For the next three years he was literally two or three weeks ahead of his students, and life was, at times, 'pretty tense'.

Gradually, the mathematical training started to show its value. Dissatisfied with much of the presentation of ideas in theoretical computing, which he found 'unnecessarily mathematical to the point where they obscured intuition', Brady set out his own perspective in his first book, 'Theory of Computer Science', published in 1975. He also became involved in research, pursuing his dream of building a machine with visual perception, using an approach partly inspired by his wife's work as a pharmacist.

At that time, the bane of any pharmacist's life was trying to decipher hand-written prescriptions. Brady was impressed by his wife's skill at this task, which he realised was operating at two levels. There was the low-level business of reading the individual characters—much helped by his wife's familiarity with the handwriting of local doctors. But this was augmented by higher-level, domain-specific knowledge, i.e. she was familiar with the names of drugs and knew the typical dosage levels. Together with his colleagues Richard Bornat (now Professor of Computer Science at Queen Mary and Westfield College) and Bob Wielinga (now Professor of Computer Science at the University of Amsterdam), Brady decided to try the same approach to the machine-based reading of hand-written Fortran coding sheets, combining low-level character recognition techniques with higher-level knowledge of the syntax of Fortran program statements.

It was 'pretty hard'. Essex had no digital cameras, and only a time-shared computer system. Coding sheets and blank tapes were dispatched to the Rutherford Appleton Laboratory, and, a week or two later, the tapes, now holding the digitised images of a single coding sheet, were returned. But, the vision program eventually worked, reading lines of Fortran that would have been impossible 'solely with a character recogniser'.

'Wouldn't it be great to build a machine that could actually see'

Brave new world

In 1975, Brady went to America to spend a sabbatical year at the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology. The AI Lab, founded in 1959 by Marvin Minsky and John McCarthy was, and is, a world-class centre for AI research. After MIT, nothing was ever quite the same again.

'I arrived from Essex, where there was not much of a research culture, and suddenly I was in this phenomenally active research laboratory. You really had a feeling things were happening. It was like a drug—just wonderful. And there was so much equipment. The average graduate student had more computing power than the whole of the University of Essex. I just looked at all the kit and thought, my God, what am I doing?'

He went back as often as his commitments to Essex and family would allow—a month in 1976 and 1977, then the whole summer in 1978. At the end of this last visit Brady was asked to join the Lab full time as a Senior Research Scientist. The paperwork took a little time to sort out, but in 1980, Brady, Naomi, and their two daughters, aged seven and nine, arrived to begin a new life in Boston.

With all that 'kit' at his disposal, Brady was soon branching out from his earlier interests in computer vision.

'As human beings,' he explains, 'we're not just seeing machines, we're seeing and acting machines.' Almost inevitably, he started a research programme in robotics—supported by 'four remarkably talented students, Tomas Lozano-Péerez, John Hollerbach, Matt Mason, and Eric Grimson—now all heroes in robotics', plus several million dollars, from DARPA, the Office of Naval Research and the System Development Foundation. The venture proved a 'phenomenal success', and Brady settled down to spend the rest of his working life in MIT.

Back in the UK, the political climate that had accepted the brain drain as an unavoidable facet of national decline was gradually beginning to change. The Alvey Programme was getting into its stride, and financial support for university science and technology departments was increased. Part of this development included a deliberate, if discrete, programme aimed at attracting key individuals back from the US. Brady was one of those targeted by this initiative, and in March 1985 he received a phone call asking him if he would like to come over to Oxford and explore the possibility of becoming Professor of Information Engineering. The subsequent visit did not provide an immediate basis for deciding between the rival attractions of MIT and Oxford. 'At Oxford there was absolutely zero activity in my field. So I thought, this is professional suicide. On the other hand, it was virgin territory—an enormous opportunity. To be honest, I wasn't bothered that much, and I'd have been perfectly happy to have stayed at MIT.' Naomi, however, was bothered. She didn't want to live in the US indefinitely and, in particular, she wanted their daughters to complete their education in the UK. Brady has a telling story about how the decision in favour of Oxford was finally made.

'We couldn't make up our minds. Then one evening I sat down with my wife, and said, "Here's a bottle of wine, by the time we've drunk it we'll have made a decision". We took one glass. "So?" said Naomi. And I said, "Hell, let's go to Oxford, it's a fantastic opportunity".' In Oxford, Brady set about the business of building his new robotics laboratory. Official support came via Alvey and the EPSRC, and this was augmented by steadily increasing levels of industrial sponsorship. One day a week, for the first six months after arriving in Oxford, Brady visited a company within a hundred-mile radius to 'find out what they were doing and to explore the opportunities for co-operation'. Within five years, there were some 90 people working in the Robotics Research Group—ten permanent academics, 55 PhD students, and the remainder post-doctoral research staff.

On the move

At MIT, he'd worked mostly on fixed robots, used for visually guided automated assembly. At Oxford, his robots started to move around, with applications in manufacturing and defence. Building a successful robot vehicle requires an extraordinary range of engineering skills. There's the modelling of the vehicle's dynamic behaviour, control theory, image and signal processing, sensor data fusion ('because no single sensor works well'), and parallel computing ('because there's no point in taking an image and then spending an hour processing it'). It was, to quote Brady, 'a classic piece of integrated engineering science, and fantastic fun'.

With hindsight, Oxford was an excellent location for a research programme in advanced robotics. Thanks, in large part, to the University's unified engineering department—one of the factors that had attracted Brady away from MIT. 'Oxford was,' he says, 'intellectually, absolutely the right place for me to be. A department that believes in an underlying core of mathematics, computing and engineering principles, which are the common basis of a whole range of applications. It was exactly what I'd been searching for all my life.'

Oxford's attractions to good research students also helped. The one lesson, above all others, that Brady brought from his time at MIT was that all the really great US laboratories are based around PhD students. Oxford, he told himself—with its international reputation, generous supply of postgraduate scholarships and indigenous stock of bright undergraduates—should be an ideal location in which to recruit 'substantial numbers of very good PhD students'. Time has proved him right. In his time at Oxford, the Robotics Laboratory has graduated over 150 PhD students, of whom Brady has graduated nearly 50 , and, today, his research life revolves around his 14 PhD students—just like he saw at MIT.

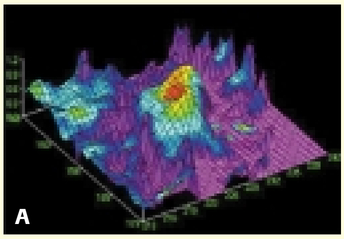
In 1989, following the sudden death of the designated appointee, Brady found himself unexpectedly 'catapulted' into the role of Head of the Engineering Science Department. Five very tiring years followed, during which Brady combined his responsibilities as Head of Department with teaching, research, membership of ACOST, and directorship of his first industrial start-up company, Guidance and Control Systems. When his five-year stint as Head of Department come to an end, Brady decided he wanted to get away for a year and to take stock of his life. He'd always wanted to learn a second language, so in 1994, accompanied by Naomi, he set off for the South of France to spend a year at the French National Institute for Research in Computer Science and Control (INRIA). They immersed themselves in French, refusing to speak English, and both became fluent French speakers. Naomi has subsequently taken a degree in French, and they now spend three months every year living and working in France.

Beneath the skin

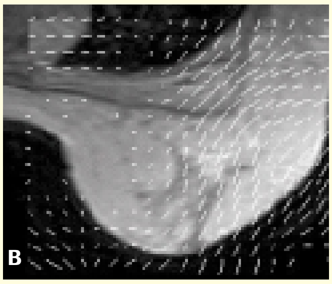
Brady's time as Head of Department was marked by a series of 'sad, personal' events that came to change the whole course of his professional career. Today, his research work is no longer dominated by robotics; instead, he has become fascinated by the challenge of bringing clarity and precision to the fuzzy, qualitative world of

Breast MRI

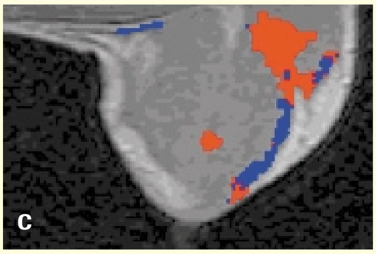
Contrast-enhanced breast MRI provides a good illustration of the ways in which Brady and his colleagues are helping to transform the capabilities of modern medical imaging.



The breast tissue of pre-menopausal women is largely opaque to x-rays, and in such cases breast MRI is preferred to x-ray mammography. Tumour sites are detected by modelling the uptake of a Galolinium contrast agent. Figure A shows a typical result, where the surface height depicts the amount of enhancement (as a percentage of the pre-contrast agent intensity), while colour indicates the speed of enhancement (red is fastest, blue and purple slowest). A drawback to MRI is the relatively long acquisition period, making some movement of the breast during the course of the scan virtually inevitable. The pattern of such movements can be identified by tracking the shifts in the boundaries of distinct anatomical features within the breast. Figure B indicates the kind of motions that result. In this case, the woman has relaxed her pectoral muscle after (naturally) being tense at the outset of the examination. A registration algorithm can compensate for such movements, producing a 'time invariant' image of the significant enhancement sites within the breast (Fig. C).



This work is fully described in Ralph Highnam and Mike Brady's book, 'Mammographic Image Analysis', Kluwer Series on Medical Image Understanding, 1999.



'There is no point in doing science if all we do is write and publish papers'

Photographs of M. Brady courtesy EPSRC

medical imaging.

It all started when his mother nearly went blind with cataracts. Her treatment seemed 'pretty crude', so Brady went to see a professor of ophthalmology to find out what was going on. Their subsequent collaboration on improving techniques of cataract detection led to two PhDs and the development of a patent, subsequently incorporated into a commercial product. Then his mother-in-law died of breast cancer. He started talking to radiologists, which led, in turn, to a ten-year research programme aimed at enhancing the role of x-rays, ultrasound and MRI in detecting breast cancer—currently Brady's biggest area of research. Finally, a favourite uncle was diagnosed as having Alzheimer's disease. He started to look around at the role of image analysis in this distressing condition, and subsequently became involved with Oxford's Department of Clinical Neurology in trying to develop MRI to help stroke victims and Alzheimer's sufferers.

The link between machine vision, robotics and medical imaging is closer than it might at first appear. First-generation medical imaging systems, i.e. conventional x-rays, provide doctors with a qualitative picture of the inside of the human body. In engineering terms, however, the images are pretty crude. Hopefully, you can see what's there, but the error bounds on the size of objects are enormous. Increasingly, however, medical staff want to use imaging in applications where measurement precision is critical. For example, in planning minimally invasive surgery and evaluating the impact of drug treatments on the likes of breast cancer and multiple scleroses.

The research programme of the Medical Vision Laboratory, established by Brady and his fellow researcher, Alison Noble, has evolved to address these new quantitative demands, following an approach broadly similar to Brady's work on machine vision, i.e. low-level image processing, a thorough knowledge of the physics of how the image was formed, combined with a total systems view to interpret the images. The benefits of this approach are evident in a recent EC-funded project looking at MRI images of the brain. This reduced the experimental error in measuring some of the complex structures in the brain from a previous best of around 30%, to less than 1%.

Under the knife

Surgical guidance provides the primary impetus for the medical application of robotics.

'Think what you need to build a mobile robot that's going to move around a factory,' says Brady. 'The robot has a nominal model of the plant in its brain, and as it moves around the plant it detects certain differences between the model and reality. You plan on the basis of what you expect to see; you begin to execute that plan with a controller in combination with real-time sensing, and you update and amend this plan in the face of unforeseen problems. Now think about what happens when you start to do surgical guidance in minimally invasive breast surgery. You have a number of images of the tumour, and these help you form a plan of the operation. You'll have an idea of where the tumour is, its size, and the epithelial activity surrounding the tumour, and your aim is to get in and cut it out. But, as you open up the breast, you find that things are not quite as you expected and you have to adjust your trajectory accordingly. This is the exact parallel of our robot vehicle finding its way around a factory.'

One of Brady's PhD students, with a project on the application of wavelet analysis of medical images to support minimally invasive surgery, has spent the last three months attending every operating session of the local breast surgeon. Not for nothing does Brady list 'a certain outwardness of spirit' as a key requirement in his research students.

Reflecting his concern with the importance of applications, Brady is a strong supporter of the view that academic engineering scientists should be involved in entrepreneurial activities. He's a non-executive director for Oxford Instruments and AEA Technology, and has launched three start-up companies of his own. Guidance and Control Systems, a spin-out of his earlier work on robot vehicles was founded in 1991, and this has now been joined by OMIA and OXIVA which owe their origins to his work in medical imaging. 'There is,' he insists, 'no point in doing science if all we do is write and publish papers.'

All this is not quite the unqualified declaration of professional contentment it might appear. At an age when many of his contemporaries are coasting towards early retirement and a decade of golf, Brady remains as intellectually involved as ever, fired by the possibilities of a new era in medical diagnostics and treatment, initiated by the advances in medical imaging he has helped to create. Discontent, it seems, is a proper condition at any age.

'I wish I was 18 again,' he now complains. 'I get to the age of 54, and I feel like a kid in a candy store. There are just so many things I still want to work on.'