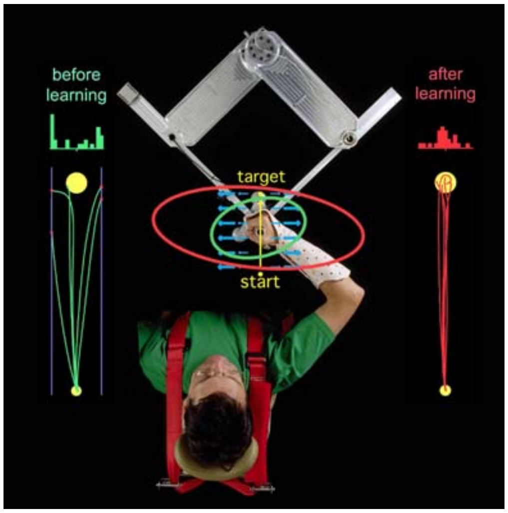
ONGOING PROJECTS

The following list describes projects already funded and started. Roughly two third of the funding was obtained from Singapore Government agencies and one third from overseas.

1. Neuroscience and Robotics

A Method to Measure Stiffness During Human Movements

Human movements are generally stable due to the spring-like property of muscles. However, movements can become unstable when the limbs interact with the environment, e.g., when one lifts a weight overhead, or carves. The stiffness measured at the endpoint of the limb is indicative of this stability. I have developed a method to measure stiffness during arm movements in collaboration with Ted Milner at Simon Fraser University in Canada and Mitsuo Kawato from ATR International, Japan. A powerful robotic interface displaces the hand during movement relative to a prediction of the undisturbed trajectory. Stiffness is estimated from the restoring force measured during the brief perturbation. Using a specially developed robot stationed at ATR, we can measure arm stiffness during adaptation to arbitrary computer-controlled dynamic environments.



Adaptation to Novel Dynamics

Our recent results on motor adaptation to arbitrary dynamics clarified how the CNS controls stable and unstable tasks. We analyzed the changes in trajectory, force, muscle activation (i.e. EMG) and endpoint stiffness in repeated movements performed in novel dynamics.

- Our results first showed that humans can voluntarily control the impedance at the endpoint of their limbs to perform stable movements in unstable situations (*Nature* 414: 446-449 (2001)). Impedance control was predicted 15 years ago, but unambiguous experimental proof was still lacking.
- Examination of the movement kinematics and EMG revealed two simultaneous but distinct mechanisms to adapt to novel (stable or unstable) dynamic environments: inverse dynamics model (IDM), compensating for stable dynamics, and impedance control providing stability with minimal metabolic cost.
- We could describe the timing and coordination of these two mechanisms when learning stable and unstable dynamics. IDM learning occurs quickly, probably facilitated by the increase of co-contraction in initial trials. Later on, the IDM is refined while impedance is optimized to provide stable motion with minimal metabolic cost.

We are currently designing experiments to investigate the brain correlates of motor adaptation to unstable and stable dynamics using fMRI compatible robotic interfaces, see below.

Unified IDM/Impedance Learning

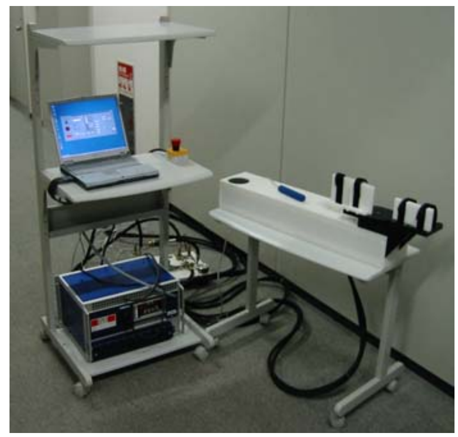
Using nonlinear control, we are developing models of human motor control that: *i*) use only measurable variables such as position, force and EMG, and are thus experimentally testable; *ii*) can give insight into the neural mechanisms involved in the above learning and be used to simulate the effect of neuro-muscular disorders on control; *iii*) can lead to better controllers for neural prostheses and robot assisted rehabilitation protocols.

We have first shown that conventional adaptive controllers, using supervised learning and minimizing endpoint or joint error, can neither learn unstable dynamics, nor reproduce the evolution of muscle activity observed in learning.

Finally, we have developed a computational model of motor adaptation to novel dynamics, that simulates muscle activation waveforms (i.e. EMG signals) during learning. This model has been validated by predicting well the trajectories, EMG and endpoint stiffness during adaptation to various stable and unstable dynamics. This model of motor adaptation is based on two distinct neural processes: i) a force process, corresponding to reciprocal activation of agonist-antagonist muscles pairs, that minimizes reflexes, i.e. signed tracking error, and ii) an impedance process corresponding to co-activation, realizing a balance between minimization of absolute error and activation, such that muscles pairs contributing less to stability are more deactivated ("looser-take-all"). We will test this model using a robotic interface in conjunction with the fMRI, see below.

fMRI Compatible Robot Technology

The main problems in creating robots that work within a MRI environment are the magnetic compatibility and limited space. In collaboration with the Swiss Institute of Technology (EPFL), we are developing a MRI compatible robotic technology, including magnetically neutral actuators and sensors, as well as hardware and software suitable to commercially available MRI. Our main concept is based on conventional electrical motors placed outside the room that hydraulically transmit power to a slave manipulator near the MRI. We have the parameters of this actuation systematically, which we are comparing with electrostatic, ultrasonic (i.e. based on piezoelectric materials), pneumatic as well as cable transmission. The modular motor module and MRI compatible sensors can be used to build robots of arbitrary architectures and applications, from haptic interfaces to infer the brain activity during motor learning to robots for minimally invasive surgery performing operations using MRI servoing. Several fMRI compatible interfaces have been realized for Japanese and European partners, and we are currently designing an interface with two degrees of freedom to study arm movements.



A fMRI compatible haptic interface with hydrostatic transmission installed at ATR

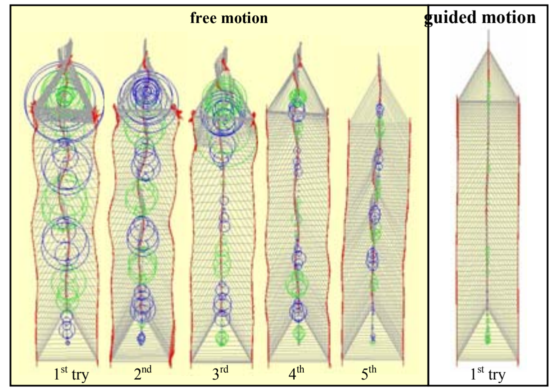
Automatic and optimal placement of neural probes

Micro-machined probes are extensively used to record impulses from various areas in the brain, and to develop neural interfaces to auditory, visual and neuromuscular prostheses. The probe has to rupture the pia matter to penetrate the underlying cortical layers. Currently the probe introduction is done in an ad-hoc manner that damages the cortical layers. Using a probe with integrated force/torque sensors mounted on a linear precision stage, this project will measure the stress and shear on the probe while penetrating the cortical layers, and investigate the related damage on the tissue. It will develop an automatic penetration procedure and devices for the probe causing minimal damage.

2. Human-machine Interaction

Evaluation of Motion Guidance by Collaborative Robots

Cobots, novel kinds of *Co*llaborative ro*bots*, have been developed at Northwestern University to assist humans in tasks involving difficult positioning, such as (re)placing a door in a car. Cobots assist humans by mechanically guiding motion over software-defined paths or surfaces. To evaluate this path guidance, we investigated representative movements of seven operators guided by the Scooter cobot. Analysis of the trajectories and of the force exerted by the operator revealed significant differences between guided movements (GM) and free movements (FM). While FM required learning for each novel task, GM was optimal from the first trial: Less energy was required to move in GM than in FM; Movements in GM were faster, smoother, and required less back and forth positioning than in FM. These advantages demonstrate the strength of the Cobot concept. The results further suggested the operators can handle objects in a more "open-loop" way when guided by the Scooter, and so perform faster and concentrate on other aspects of the manipulation task, potentially resulting in increased productivity and fewer injuries.

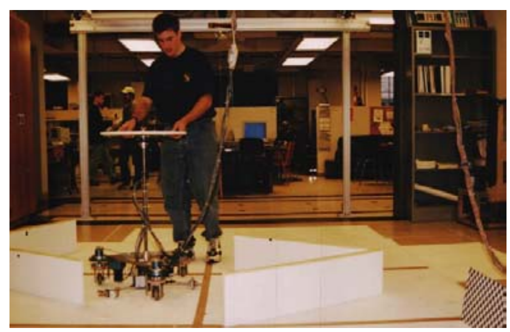


Torque magnitude (green and blue circles) for movements in free and guided mode

The Learning Cobot

Cobot kinematics, design and control have been widely investigated, and several planar and spatial cobots have been realized for the automotive industry at Northwestern University. However, it is not clear how to find ergonomic paths for the cobot to guide the operator's movement. We developed tools enabling an operator to design ergonomic guiding paths, and tested their efficiency in psychophysical experiments.

In contrast to conventional methods developed for mobile robotics, our method does not require knowledge of the environment, costly sensor processing or any optimization algorithm. Our idea is to let the operator use his/her well developed sensing and inference capabilities to design and modify the guiding path. In this approach, the cobot only has to provide the operator with simple ways to design suitable paths. The operator can define a guideway using *Walk Through Programming* (WTP), i.e. physically trace a path in free mode, which will be approximated with cubic B-splines and used as a guiding path in subsequent motions. Guideways can also be defined or modified by placing or shifting B-spline control points on the *dedicated Graphical User Interface* (GUI) with a computer mouse. *Elastic paths* enable an operator to react to changes during movement: The operator can deform the guiding path by pushing against it with sufficient force. If the environmental change is persistent, the path modification can be integrated for subsequent trials. Psychophysical experiments demonstrated the efficiency of these tools to design ergonomic paths and adapt to environmental changes. They also showed the necessity of all of these tools. Used alone, WTP was significantly more efficient than GUI. However the users liked to use the GUI and performed slightly better using both tools together.
(see also http://guppy.mpe.nus.edu.sg/~engp1647/).



Collaborative learning of an operator and his cobot

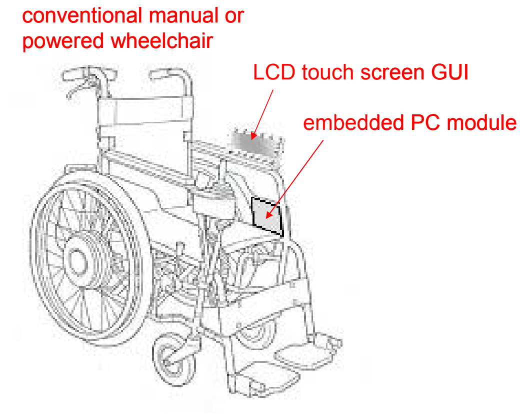
Collaborative Wheelchair Assistant

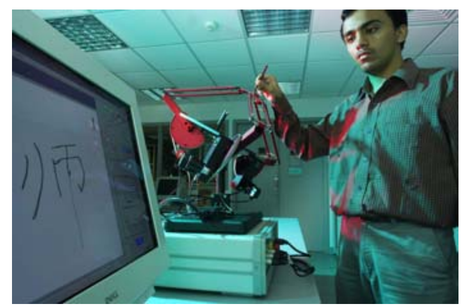
Due to physical or neurological disabilities, many wheelchair users have problems in orienting themselves and maneuvering the wheelchair especially in congested environment. They are dependent upon others to push them, making them feel powerless. The collaborative wheelchair may help these people to regain autonomy, by providing guidance along paths defined in software, while allowing them to vary the level of autonomy to suit their ability.

The only physical differences between a collaborative wheelchair and the conventional wheelchair it is derived from are the microcomputer to control the velocities of the back wheels and the touch screen LCD panel to help the user to program the guiding paths.

We are currently realizing a prototype wheelchair assistant using a Yamaha JW-I on which we implement the Learning Cobot strategy described above. We will evaluate this low-cost technology in collaboration with the Singapore National Institute of Neuroscience (see http://guppy.mpe.nus.edu.sg/~engp1647/).

In collaboration with A*STAR I^{2}R, an infocomm Singapore National Institute, we will investigate how EEG and path guidance can be combined to efficiently control the collaborative wheelchair.





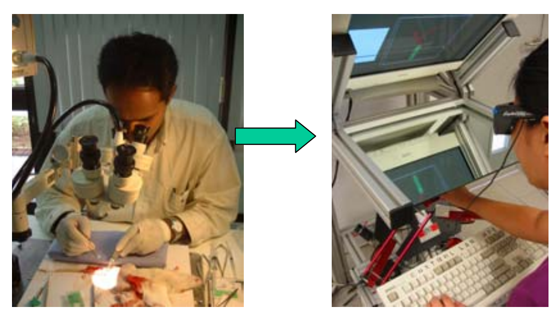
A robotic teacher of Chinese ideograms (to study motion guidance strategies)

Haptic and Visual Membranes for Real-time Simulation of Tissue and Organs

We develop a novel multi-scale method fulfilling the antagonistic requirements of a simulator with visual and haptic feedback: slow global update of the image at 60*Hz* and local but fast update of the force at 1000*Hz*, as to feel fine texture of the tissue.

To date, no algorithm exists to realize the physics of membranes at 1*kHz* and with the flexibility required in biomedical applications. Direct estimation of the geometrical content of bending tensors from a multi-scale triangulated scatter of points on the surface can compute fast mechanics for surfaces that can be assigned stress/strain relations from measured elastic properties. Moreover, it allows dynamic scale variation across the surface, modeling it in detail near the haptic tool tip, coarsely at a distance, reducing computation time by orders of magnitude while still reporting forces appropriate to the global form of the surface.

This project is a collaboration between the Mechanical Eng. Dept of the NUS and John Hopkins Singapore (www.jhs.com.sg).



In future, current microsurgery training on rats could be completed by training on a VR workstation

Training and Testing Dexterity in Micromanipulation

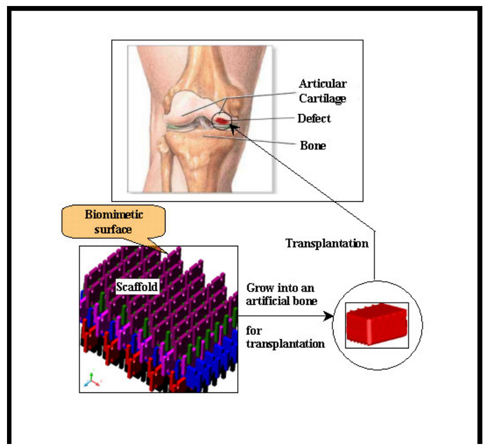
A microscope as used by a microsurgeon enlarges tenfold what the surgeon's eye sees, but the hands must still make microscopic motions. The microsurgeon in training must learn the modified visuo-motor coordination, and to work with tools instead of with the fingers. To help training manipulation under optical microscope, we are developing, in collaboration with Johns Hopkins Singapore, a Virtual Reality based training system as a tool for hand microsurgeons at the National University Hospital.

Studies suggest that humans may form internal models of these primitives which they can combine in more complex tasks, so that when this task is decomposed and learned in simple steps than all at once, learning a complex task can be faster and performance better.

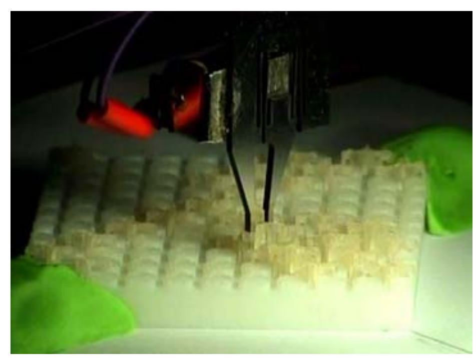
Therefore, our approach consists of decomposing representative tasks, such as accurately joining the two vessels or knot tying, into simple dexterity primitives, that will be learned using suitable multisensory cues. We use multisensory cues based on neuroscience results. In particular, we have recently shown that motion and path guidance can facilitate learning hand motion for Chinese handwriting and for object handling. We have also discovered that humans respond to unstable dynamics with neural strategies for improved accuracy. We will test how these haptic cues, as well as amplified tremor, can help micromanipulation learning. Audio signals related to trajectory error relative to a desired movement will be used as audio cues. We will investigate predictive visual cues that compensate for the long delay in the visual loop.

3. Microrobotics as a Tool for Life Sciences

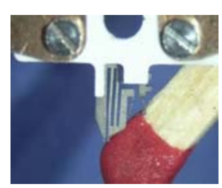
Robotic Micro-assembly Fabrication of 3-D Scaffolds for Tissue Engineering

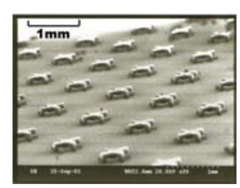


Tissue engineering is based on the concept that cells seeded onto three-dimensional bioresorbable scaffolds can recapitulate native tissues under appropriate in vitro and in vivo conditions. So tissue engineering may soon provide an alternative to tissue and organ transplantation. This project is developing innovative micro-manufacturing techniques and using them to fabricate a novel scaffold for Tissue Engineering. Our idea is to form scaffolds by assembling microscopic building blocks of resorbable polymer. In this way, it will become possible to control the distribution of chemicals and living cells inside the scaffolds and so to facilitate the formation of tissue around the scaffolds and their gradual replacement. Building blocks (with overall size 600x600x200μm and width 60μm) made of (biocompatible photoresist) SU-8 have been designed using lithography. These microscopic blocks are assembled with visual servoing using two optical microscopes. We use a specially designed shape memory alloy microgripper (developed with the Swiss Institute of Technology (EPFL), and a (x,y,z,θ)-table, to manipulate the microparts at a precision of a few microns. The fabricated scaffolds will be investigated for their use in Tissue Engineering. This is a joint project of NUS and the Singapore National University Hospital (http://guppy.mpe.nus.edu.sg/~hzhang).



3-D Plotting Fabrication of Scaffolds for Tissue Engineering





The aim of this project is to develop a microrobotic workstation with dispensing system to fabricate 3D scaffolds for tissue engineering. In contrast to existing systems, it will be possible to introduce the growth factors and living cells into the material so as to control their distribution in the scaffold and provide optimal growth conditions. It will also become possible to produce scaffolds with different architecture and cell types for each layer and section mimicking the anatomical features of the natural tissue/organ, using multiple feeds.