

ARC CENTRE OF EXCELLENCE FOR  
AUTONOMOUS SYSTEMS

# COBOTICS FOR MEAT PROCESSING

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AN INVESTIGATION INTO TECHNOLOGIES  
ENABLING ROBOTIC ASSISTANCE FOR  
WORKERS IN THE MEAT PROCESSING  
INDUSTRY

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## INTRODUCTION

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This report is an investigation into technology which has the potential for application in the meat processing industry, in particular as an aid to human operators. The aim is to find ways of reducing the stress on the bodies of workers in the meat industry, resulting in reduced rates of injury, and reduced rates of worker turnover. It is also hoped that such assistive technology may enable tasks in meat processing to be opened up to workers with a wider range of physique.

The focus of the report is on a relatively new branch of robotics called *Cobotics*, and on a wider class of devices known as *Intelligent Assist Devices* (or IADs). These devices have the principal characteristic of human operators working in direct contact with mechanical devices which provide guidance, force support (or amplification), and maintain safety boundaries. We also discuss technology connected to *Teleoperated Robots*. While teleoperation is unlikely to be a viable option for direct application in the meat industry in the short term, the enabling technology is closely linked to Cobots and IADs, and may have an important contribution to assistive technology.

### COBOTS

*Cobotics* is a term coined in the 1990's by Professors Edward Colgate and Michael Peshkin of Northwestern University [Peshkin96]. A *Cobot* is defined to be a

*robot for direct physical interaction with a human operator, within a shared workspace.*

The term is derived from “collaborative robot”, and indicates that cobots are designed to interact very closely with human operators. This is in stark contrast to the typical use of modern industrial robots, where fully automated tasks are undertaken with very little human intervention.

According to the strict technical definition, a cobot is a passive device. That is, artificial forces introduced are strictly resistive and do not do work. Any active forces must be applied by the operator.

The distinguishing features of cobots are software-defined *virtual surfaces* and control mechanisms which constrain and guide the motion of the payload. A virtual surface is in many ways analogous to the straight edge in drafting. Drawing a freehand straight line is difficult and slow. The use of a straight edge has the effect of removing a degree of freedom from the pencil, enabling the task to be accomplished quickly and easily. Similarly, a cobot virtual surface removes one or more degrees of freedom from the motion of the payload. This allows the operator to concentrate effort on the remaining degrees of freedom, accomplishing tasks more quickly and with greater precision.

Cobots have several advantages over fully autonomous robots, especially when the sensing tasks are very difficult. Cobots take advantage of the sensory perception and spatial awareness skills of a human operator.

Where a cobot assisted operator takes the place of an unaided operator, the result should be:

- greater efficiency and speed of operation,
- greater performance in precision tasks,

- higher margins of safety, and
- reduced rates of operator injury due to wear and tear.

### INTELLIGENT ASSIST DEVICES

*Intelligent Assist Devices* (or IADs) are a wider class of devices that include cobots. The class (like cobots) describes mechanical devices for direct interaction with human operators. The difference is that IADs include fully active devices in which the device can amplify the force applied by the human operator. As in cobot operation, the direction of an IAD (subject to constraints) is fully under the control of the operator, however the force amplification enables the aided operator to apply much greater forces than an unaided operator, or to apply similar forces with much less effort.

It is this broader class of devices, in particular the active devices which have the greatest potential for application in the meat processing industry. This is because the active devices enable operators to achieve the same tasks with lower effort, and hence also open up tasks to people with a wider variety of physique.

The review paper [Colgate03] provides a useful overview of some recent industrial applications of IADs. The applications discussed are all variations on lifters and manipulators, and are intended for the transport and placement of bulky and heavy payloads.

The use of force amplification in lifter applications enables large loads to be handled by a single human operator without particular physical strength. Force amplification in manipulator applications enable large loads to be moved quickly and easily by the operator, as the IAD both supports the weight, and compensates for the friction and inertia of the load. The virtual surface aspect of the IAD enables the payload to be placed quickly and precisely using the surfaces as guides.

The term cobot is sometimes used to refer to IADs which are active rather than passive devices. Some of the commercial IADs for material handling are referred to as cobots even though they are devices for force amplification and support. In the remainder of this report, we will permit the use of the term cobot to refer to active devices, and will use the terms *passive cobot* and *active cobot* where the distinction is necessary.

### TELEOPERATED ROBOTS

A teleoperated robot is a mechanical device which is operated from a separate location by a human operator. The operator receives sensory information (usually visual) from the device or the environment, and usually has direct authority over the robot motion. Automatic control is typically restricted to tracking of operator reference commands. Since the robot can be operated from a remote location, safety can be guaranteed by restricting human access to the robot operation area.

Teleoperated robotics has a long history in manufacturing and cargo handling, and today plays an important role in a wide variety of industries including healthcare, nuclear power, aerospace, defence and search and rescue.

Teleoperation applications can be greatly enhanced by the use of *haptic* interface devices. Haptic devices enable the operator to receive tactile sensory information from the manipulator in addition to other forms of feedback. The tactile feedback can be straightforward force feedback, where the operator feels forces on the interface device which reflect forces on the remote manipulator. Tactile

feedback can also involve very complex tactile sensations, requiring the use of haptic gloves or immersion suits.

The technology of cobotics is closely related to teleoperation. The primary distinction is that the operator of a cobotic system is typically directly in contact with the robotic manipulators rather than operating them from a remote location. In a cobotic system, the manipulator and interface are merged into a single device.

While the potential for direct applications of teleoperated robots in the meat industry seems to be quite limited, there are technological aspects of teleoperated robots (especially haptic interfaces and force feedback) which may play an important role in a cobotic approach.

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## ROBOTICS IN THE MEAT PROCESSING INDUSTRY

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Robotics has been investigated for applications in red meat industry. Several robotic systems have been developed and applied such as Y-cutter developed by IRL (Industrial Research Limited, [IRL02] and [MAR]), leg-boner [MAR], loin boner and spine removal [MACPRO], pelt puller [SFK], etc. Many other projects are under development, either in research and development stage or in commercialization stage. Examples includes robotic carcass splitting, robotic scribing, robotic De-Dagging, various semi-automated beef boning machines, automatic robotic caul/kidney fat removal, robotic carcass cutting (head saw), small stock bell rip and brisket cutting and so on [MLA04].

Sensing, the detection and measurement of bones hidden in carcass, position, geometry and size of bones are the most difficult problems in robotic applications in the meat industry. Also, the complex motions and forces required in some meat processing operations make it difficult for a robot to match the productivity of a skilled manual operator. Carcass stabilization during the boning operation is another potential difficulty. There are possible methods for fixing the carcass, but they may limit the movement and rotation of the carcass required during conventional boning operations.

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## PASSIVE COBOT APPLICATIONS

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We discuss here some applications (some commercial and some prototype) of (passive) cobotic technology.

### "UNICYCLE" COBOT

This is the simplest possible architecture of a cobot consisting of a single wheel steered by a motor. The cobot is able to demonstrate the two essential control modes: "free" mode in which the wheel is steered such as to comply with the user's desired direction of motion, and "constraint tracking" mode in which the wheel is steered such as to confine the user's motion to a software-defined guiding surface. In line with the steering axis of the wheel is a force sensor, which is only required to determine  $x$  and  $y$  forces for this cobot [LIMS].

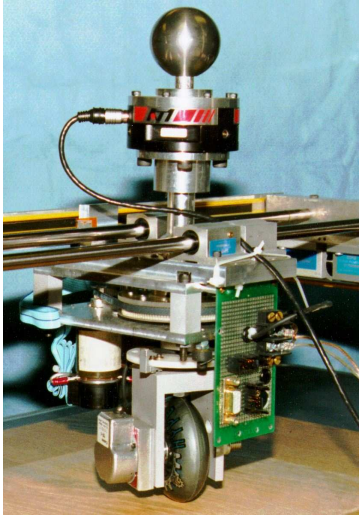


Fig.1 a unicycle cobot

### SCOOTER

This is a three-wheeled cobot that resides in a plane like the unicycle device, but is allowed to rotate and thus has a usable three-dimensional task space. In "free" mode, Scooter can allow arbitrary motion in three coordinates:  $x$ ,  $y$ , and  $\theta$ . Scooter can also display software-defined guiding surfaces which are one or two dimensional [LIMS].

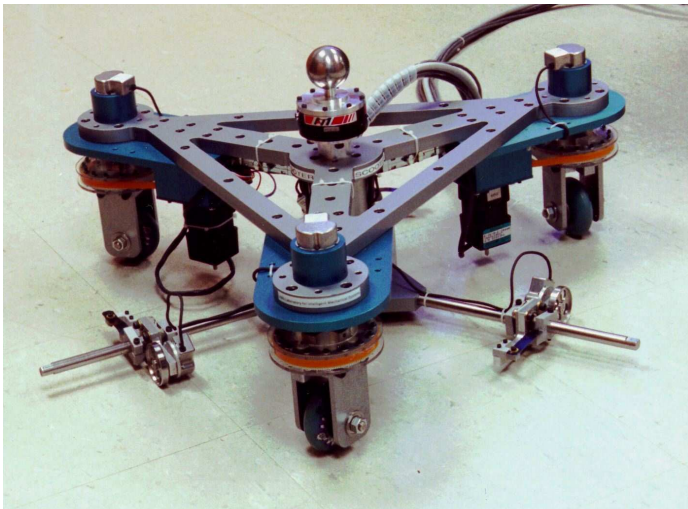


Fig.2 a Scooter cobot

Two modifications of this cobot have been reported: (a) a learning cobot and (b) a pallet jack cobot [Faulring02].

An easy and efficient method to define a good ideal path is the focus of the learning cobot. A path optimal to one person may not be optimal to another due to different personal preferences and physiques. A teach pendant is used to define the ideal path. The scooter hence *learns* from its operator what the ideal path is [Boy03].

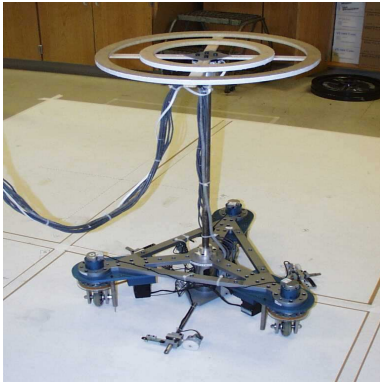


Fig.3 a learning cobot

A Pallet Jack system typically does not have more than one steerable wheel (mechanically linked to the handle) and have no automated docking or path tracking modes. The addition of a handle to the Scooter is for the purpose of investigating what intelligent three wheel steering modes and automated docking and path tracking modes might be advantageous. The transition between a "free" mode and a "constrained" mode is also interested in this research.



Fig.4 a Pallet Jack cobot

An important component in a cobotic system is a Continuously Variable Transmission (CVT). It is used as a revolute joint in armlike cobots. Fig.5 shows a "**Tetrahedral CVT**" [Moore97]. The angular velocities of the two shafts on the left are coupled via a transmission ratio which is set by the angle of the steering rollers on the right. This device is the analog of the rolling wheel that is used in translational cobots such as Scooter. Wheels are appropriate for translational motions, but arm-like cobots (having the architecture of today's arm-like robots) will need a device appropriate to revolute motion.

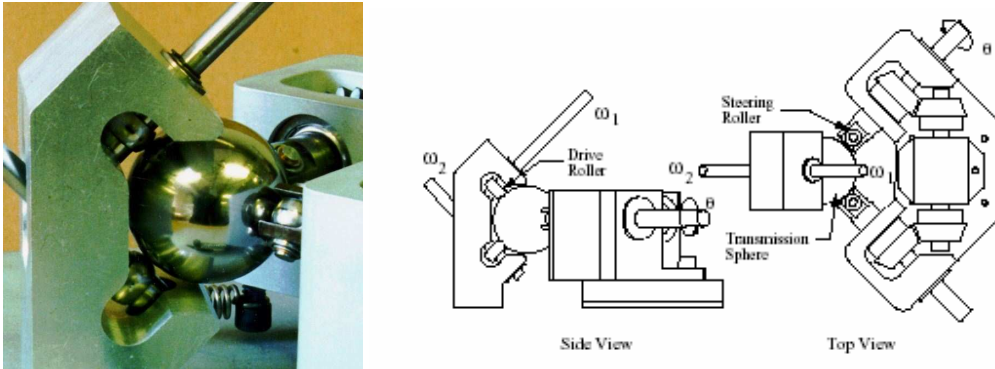


Fig.5 a "Tetrahedral CVT"

### ARM COBOT

This cobot uses three revolute joints coupled by three CVTs in the base [Moore01]. It consists of a two degree of freedom parallelogram linkage allowing motion in a vertical plane. This linkage (vertical plane) is allowed to rotate about a vertical axis, thus providing a third degree of freedom. All three degrees of freedom are coupled via revolute joints to spherical continuously variable transmissions (CVTs), which in turn are coupled to a single common power wheel. The contribution of the arm cobot is its ability to create virtual paths and virtual surfaces in a large region of  $x$ - $y$ - $z$  Cartesian space.

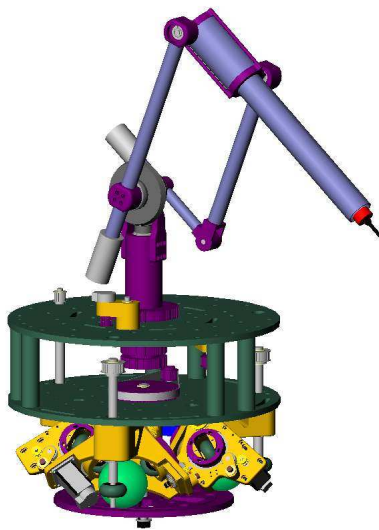


Fig.6 an Arm Cobot

### DOOR UNLOADER

This is a scooter-like cobot at General Motors [Akella99]. This passive cobotic tool takes doors off of vehicles. It consists of a “cobot” module to control motion across the plant floor and a task specific “tooling” module to grasp and lift the door off. The removal process is a problematic one due to tight tolerances, highly curved body surfaces, and the need for vehicle specific “escape trajectories” to avoid damage to any surfaces visible to customers.





Fig.7 a Door unloader cobot

#### A HIGH PERFORMANCE 6-DOF HAPTIC COBOT

This is a novel, six-degree-of-freedom input device for use with teleoperated robots. A parallel kinematic design and the use of continuously variable transmissions provide high stiffness in directions that would violate a virtual constraint. At the same time, smooth motion is permitted tangential to virtual constraints and in open space. High quality constraint surfaces having one to five dimensions can be displayed. A notable feature of this device is the mutual coupling of all six linear actuators to a common rotating cylinder, which can, optionally, be powered. The resulting mechanism is simple to control, and allows new control strategies in Cobot haptics [Faulring04].

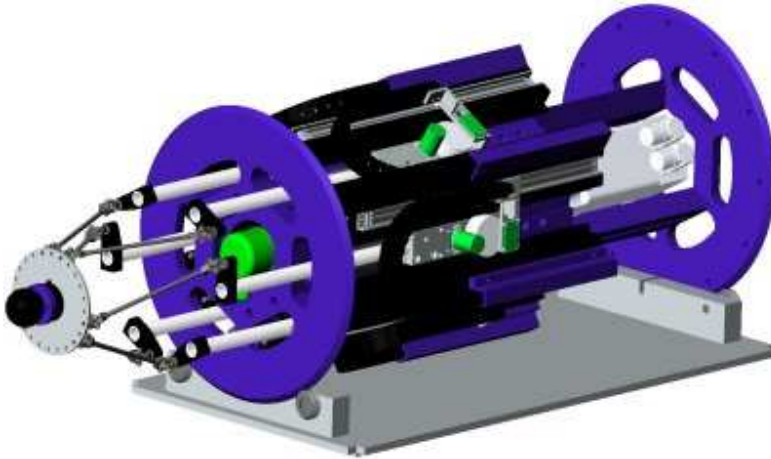


Fig.8 a Haptic cobot

The Unicycle Two-Link Arm (UTLA) (Fig.9) is a one-wheeled, two degree-of-freedom (DOF) cobot that consists of two links and two rotational joints connected to a fixed reference frame. Located at the end of the second link are a handle and a wheel that supports the cobot. There is a force sensor located beneath the handle. This is used for rehabilitation purposes [Worsnopp04].

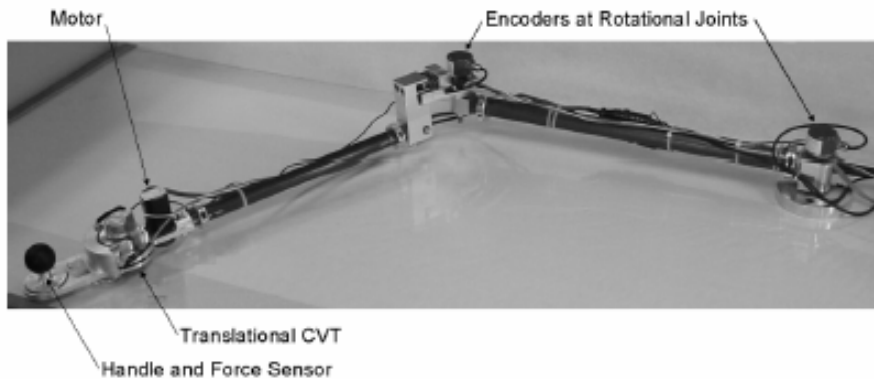


Fig.9 a Unicycle Two-Link Arm (UTLA)

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### ACTIVE COBOT APPLICATIONS

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We discuss here some current applications of active cobots, or intelligent assist devices.

#### PRODUCTS AVAILABLE AND UNDER DEVELOPMENT

##### ITROLLEY: RAIL-BASED, POWER-ASSIST COBOT

The iTrolley cobot (manufactured by Stanley Assembly) is a commercially available product, and installed at Ford Motor Company's Advanced Manufacturing Technology Division. Passive overhead rail systems are very popular in automobile final assembly plants, as well as in many other applications in materials handling. A rail system may be converted into a cobot by the addition of CVT elements which are adjustable under computer control, and a sensor which is used to monitor the user's applied force. It can also allow the addition of a limited amount of "power assist" to help the user overcome the inherent friction of the rail system. Three benefits accrue from the conversion of a passive rail system to a cobot: (a) the inherent **friction** of the rail system can be reduced essentially to zero; (b) the **anisotropy** of the passive rail system's response to the user's forces can be eliminated. This anisotropy is due to the difference in mass of the moving parts when moving in the x and y directions, and (c) **virtual surfaces** provided to guide the user's motion under computer control [Stanley] and [Akella99].

This device belongs somewhat on the boundary between active and passive systems. The active devices are used only in a limited fashion to counteract the friction of the rails, and to reduce the apparent inertia of the payload.

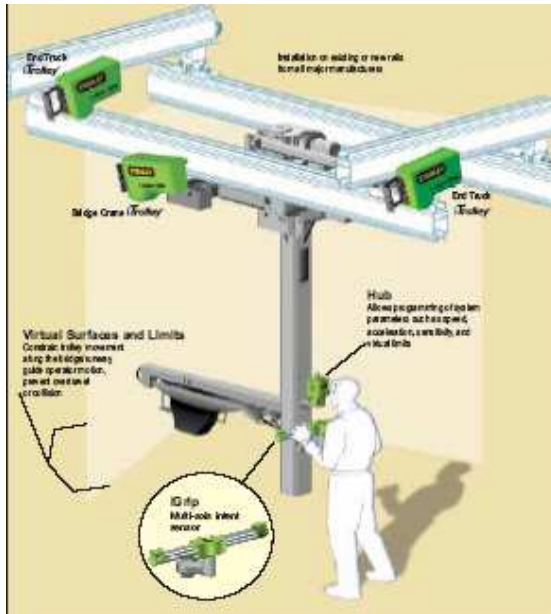


Fig.10 Rail-based cobot [Stanley]

#### ILIFT: POWER ASSISTED LIFTER

The Stanley iLift [Stanley] is a fully active power assisted lifting device. The operator controls the vertical position of the load via a vertical “slider” which is attached to the end effector. The power assistance is strictly one dimensional, however the system can also be used in conjunction with standard rail systems of the iTrolley (see above) to obtain additional degrees of freedom. The two main models of iLift are capable of handling loads of 68kg and 226kg respectively at lift speeds of up to 1.5m/s and 0.7m/s.

The iLift and iTrolley were developed initially by the Cobotics company, which was recently acquired by Stanley.

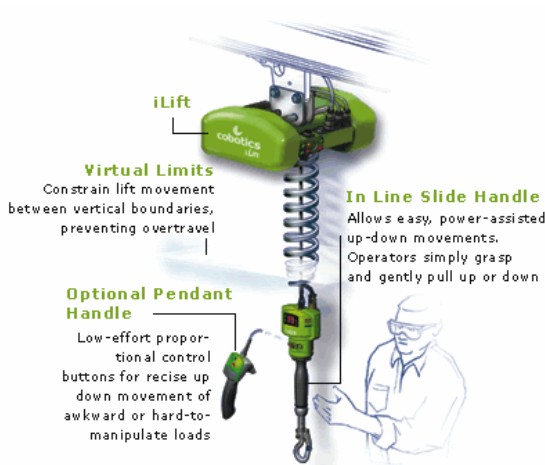


Fig.11 iLift [Stanley]

## GORBEL G-FORCE



Fig.12 Gorbel G-Force [Gorbel]

The Gorbel G-Force [Gorbel] is apparently very similar to the Stanley iLift (though with somewhat lower specifications). The device (depending on the model) is capable of lifting up to 140kg load at approx 0.5m/s, or 70kg at 1m/s. A Gorbel conducted study [GorbelStudy] found substantial advantages in using the G-Force for palletizing applications compared to conventional devices. Comparisons were made to devices such as an air balancer with pendant control, a variable frequency chain hoist, an electric balancer and an air balancer with electric controls, and manual lifting. Advantages found included greater number of lifts per time, lower operator force for lifting (and reversing direction), lower operator energy expenditure, lower placement force (reduced danger to the payload). We expect that similar results would be observed comparing the Stanley iLift to standard devices.

## POWERMATE

Researchers at the Fraunhofer Institute for Manufacturing Engineering and Automation have developed an innovative robot arm for handling and assembly tasks [Schraft05]. The *PowerMate* is designed to be used in both autonomous and assistive mode. In autonomous mode, the robot can perform normal robot manipulator tasks at high speeds. In assistive mode, a human in direct contact with the end effector guides the robot (operating at very low speeds) for high precision tasks.

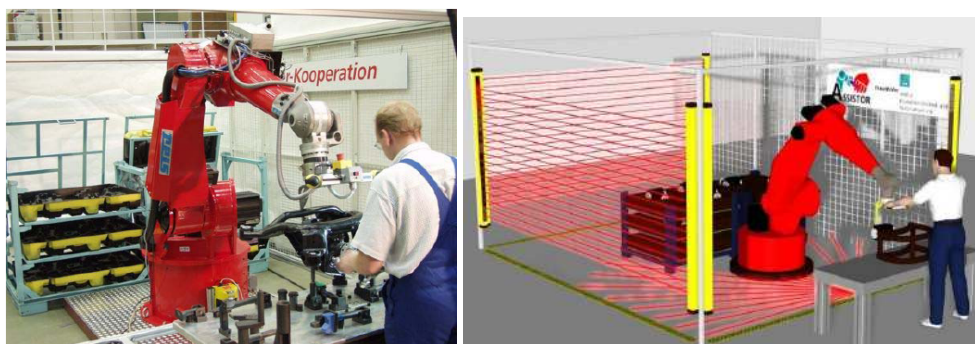


Fig. 12a *PowerMate* assistive robot in operation. 12b Schematic view.

The *PowerMate* is still in the prototyping stage, but it seems to be very close to industrial implementation in handling and assembly tasks.

The researchers at Fraunhofer have taken particular care over issues of safety. Autonomous operation of the robot occurs in an exclusion zone (see fig 12b), while operation outside the exclusion zone requires the user to make two handed contact with the robot, holding down a release switch. The robot speeds are also restricted to 25mm/s while in contact with the human operator.

The Fraunhofer researchers have developed fruitful relationships with safety authorities in Germany. The *PowerMate* is an entirely new type of device for industry, and requires the development of new safety guidelines and certifications. The relationship between Fraunhofer and government authorities could potentially be a model for similar relationships in other countries.

### MECHANICAL EXOSKELETONS

One of the limitations of many of the cobotic applications described so far is that they nearly all require a fixed mounting point in the environment. The main advantage of such a fixed mounting point, is that forces imparted by the device may be transmitted through the mounting so that they are not perceived by the device operator. The disadvantage, of course is that the range of motion of the device is restricted to within a certain radius of the mounting point. The mounting can also be quite bulky, and needs to be designed carefully to avoid restrictions on the motion of the operator and payload.

Mechanical exoskeletons have existed in concept and prototype form for over 40 years. They overcome the mounting point problem by mounting the mechanical device directly on the human body (or by situation the operator “within” a fully mobile device). The concept is familiar to most people through the film “Aliens” in which the protagonist fights the climactic battle wearing a mechanical exoskeleton which was designed for materials handling.

The first serious attempt at exoskeleton design was the General Electric research device “Hardiman 1” in 1965. The device was as heavy as a car, and designed to allow the operator to lift loads of up to 500kg. The project was far from successful however, as the inventors were only ever able to get one arm working, and attempts to use both legs resulted in “violent and uncontrollable motion” [Weiss01].



Fig.13 Mechanical exoskeleton

More recent attempts at exoskeleton have been far less ambitious, but also more successful.

The US Defense Advanced Research Projects Agency has established an \$80 million fund for research and development of robotic aids for soldiers. Exoskeleton research is an important

component, and is managed by Dr Tony Main in the Exoskeletons for Human Performance Augmentation (EHPA) program. DARPA are working towards a concept of soldiers wearing “smart suits” which provide mechanical augmentation, as well as extra sensing and perception capabilities.



Fig.14 “Smart suits”

Some of the collaborative research projects funded by DARPA are described below.

#### OAK RIDGE NATIONAL LABORATORY

The Oak Ridge National Laboratory (ORNL) Robotics and Energetic Systems Group have been conducting research into human exoskeletons under the direction of Dr Francois Pin (and funded by DARPA). Single leg amplification prototypes have been tested, but publicly available information is limited. ORNL aims to produce a fully functional exoskeleton within the next three to five years.



Fig.15 a single leg amplification prototype

#### BERKELEY LOWER EXTREMITY EXOSKELETON

The University of California at Berkeley have developed a lower extremity exoskeleton (BLEEX) in conjunction with DARPA. The prototype device is intended to assist soldiers in carrying very heavy loads over long distances. The force assistance is hydraulic, and is powered by a small internal combustion engine (carried in the required backpack along with the computing system). BLEEX was demonstrated at a DARPA Technical Symposium in California in March 2004.

This device, while demonstrating the feasibility of exoskeleton devices for operator assistance is quite a long way from being a practical reality in the field. The prototype weighs an astonishing 50kg, with capacity for an additional 32kg in payload. The internal engine is also extremely noisy. In publicly available video footage, it also appears that the current prototype requires an external air supply hose.



Fig.16 BLEEX

#### HYBRID ASSISTIVE LIMB (HAL)

A very recent development is the Hybrid Assistive Limb (HAL) Project emerging from the University of Tsukuba in Japan. The current version HAL 3 is a lower limb exoskeleton, which is designed to assist walking for those with very weak lower limbs, or to provide assistance in carrying heavy loads.

This system uses biometric sensors to detect electrical signals carried by the nervous system in order to direct the operation of the assistive device. It is reported that the response time of the biometric sensors are of a similar order to the response times of human muscles. It is also relatively compact compared to other prototype exoskeleton (at 22kg, it is considerably lighter than the BLEEX with the models 4 and 5 expected to be more compact again), but does require the user to carry a backpack containing some system components.

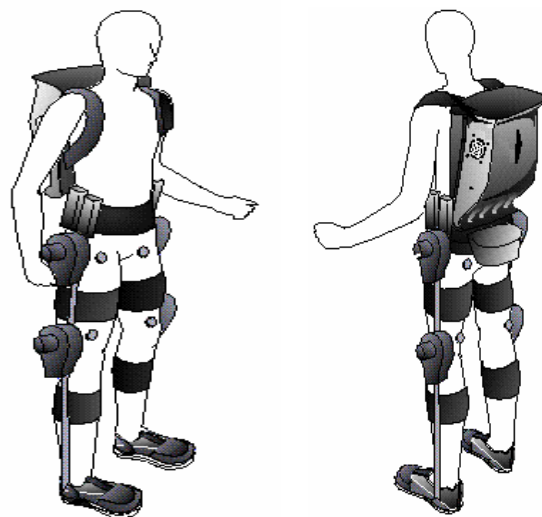


Fig.17 Hybrid assistive limb 3

The latest versions of this device HAL 4 and 5 are due to be launched this June at the 2005 World Expo in Aichi, Japan. They are reported to incorporate an upper body exoskeleton for



carrying heavy loads, and also to omit the need for a backpack to be worn to carry the relevant computer hardware.

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## TELEOPERATION APPLICATIONS

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There have been a very large number of teleoperation applications in the last fifty years. Teleoperated robots are motivated by one of a number of factors:

- hazardous materials (e.g radioactive material, toxic waste and biohazards)
- hazardous environments (e.g outside a space shuttle, deep underwater)
- remote environments (e.g satellites, Martian exploration, other unmanned vehicles)
- environments with limited access (e.g laparoscopic or endoscopic surgery).

We will not discuss all of these applications here, but instead examine a few recent applications which include technology which may influence future cobotic technology.

## MEDICAL APPLICATIONS

### DA VINCI® SURGICAL SYSTEM

(all images in this section copyright Intuitive Surgical®)

The *da Vinci* system by Intuitive Surgical® (<http://www.intuitivesurgical.com/>) is the leading system for robotic surgical assistance currently available in the marketplace and with approval for surgical use. It is a teleoperated mechanism, and provides up to four independent robotic arms (one endoscope and three manipulators) and a haptic hand interface for the surgeon operating the device. The system enables complex procedures to be undertaken through very small incisions in the patient's body that would otherwise require open surgery. The system received approval from the US Food and Drug Administration (FDA) for use in laparoscopic and thoracoscopic procedures in 2000 and 2001 respectively).

The Surgeon Console allows the surgeon to operate while seated comfortably at a console viewing a 3-D image of the surgical field. The surgeon's fingers grasp the master controls below the display with hands and wrists naturally positioned relative to his or her eyes. The technology translates the surgeon's hand, wrist and finger movements into precise, real-time movements of the surgical instruments inside the patient.



Fig.18 a surgeon console



The Patient-side Cart provides two or three instrument arms and one endoscope arm - that execute the surgeon's commands. The laparoscopic arms pivot at the 1-cm operating ports eliminating the use of the patient's body wall for leverage and minimizing tissue damage. Supporting surgical team members assist in installing the proper instruments, prepare the 1-cm port in the patient, as well as supervise the laparoscopic arms and tools being utilized.



Fig.19 a patient-side cart

**da Vinci® Surgical System in a Cardiac Procedure Setting**

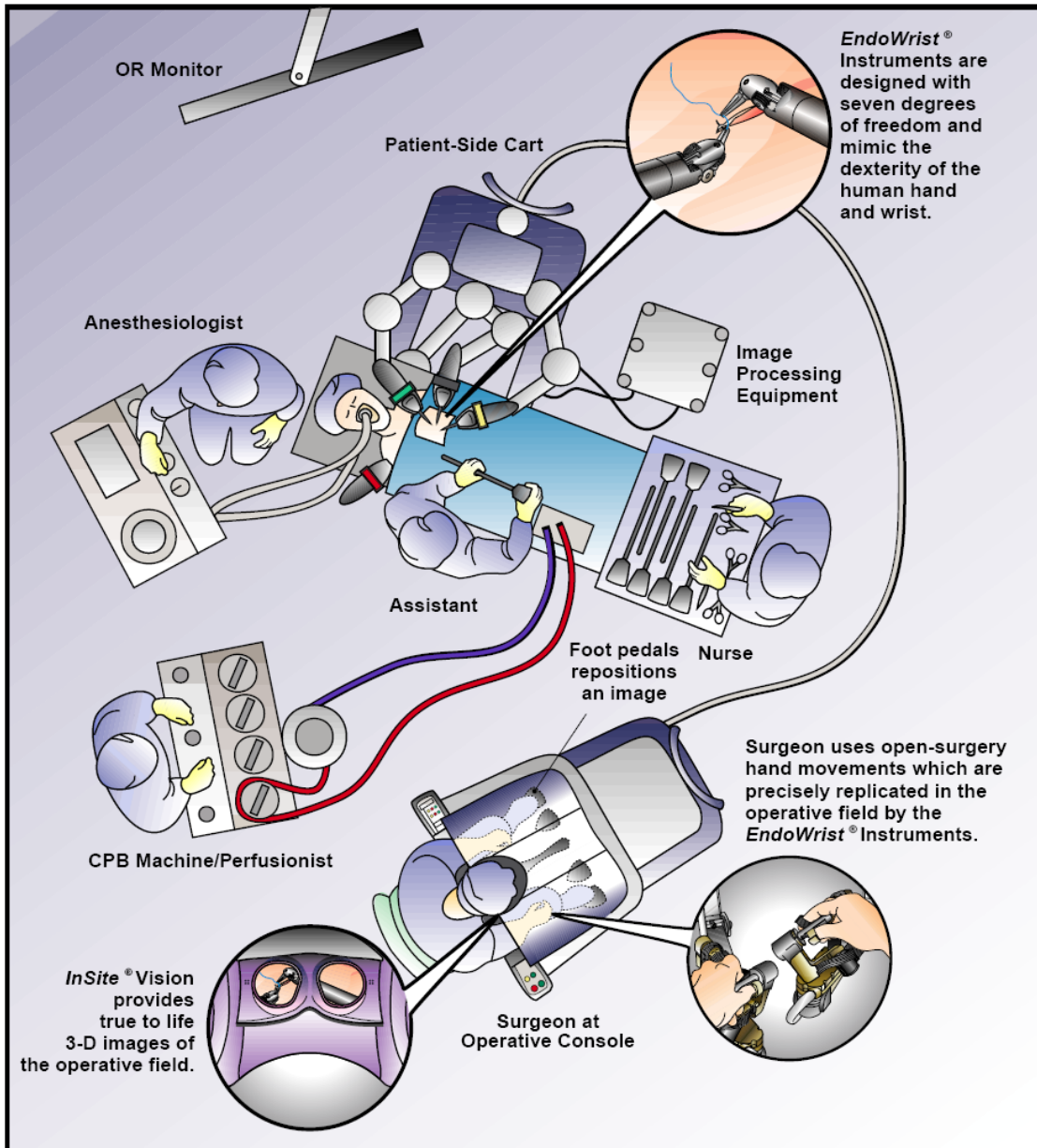


Fig.19 da Vinci® surgical system in a cardiac procedure setting

**ZEUS® SURGICAL SYSTEM**

The ZEUS® surgical system by Computer Motion (approved by the FDA in 2001) was formerly a competitor to *da Vinci*, however Computer Motion merged with Intuitive Surgical in 2003, and the ZEUS system is no longer available. The ZEUS system is similar in concept to *da Vinci*, consisting of two robotic manipulators which are directly controlled by the surgeon, and a voice controlled endoscopic arm carrying the camera which returns visual information to the surgeon. The ZEUS system is still in use by a number of surgical teams around the world.

## HAPTIC DEVICES

Haptic interface technology is a rapidly growing area. While Haptic devices have been around for many years, there has been rapid growth in the number of commercially available devices in the last five years. There is also a solid body of academic research in the area of haptic devices and force feedback.

Mature commercial haptic devices mostly take the form of either virtual reality aids such as gloves, where the feedback is touch sensitive but does not convey a large range of force information (sometimes vibration only); and force feedback devices such as joysticks and stylus (often available with a full 6 degree of freedom range of movement). It is the latter group of force feedback devices that are most closely connected with cobotics.

### PHANTOM FORCE FEEDBACK STYLUS

Sensible Technologies have a range of force feedback devices in the PHANTOM® product line [Phantom]. The products range from 6DoF position only devices, through to devices intended for industrial design, with 6DoF positioning and 6DoF force feedback. The premium devices are capable of up to 8.5N in translational force feedback, and up to 500mNm and 170mNm rotational force feedback (pitch/roll and yaw respectively) [Cohen99].



Fig.20 force feedback devices

### IMMERSION DEVICES

Immersion Corporation has a range of interesting haptic devices [Immersion]. The devices are mainly intended for virtual reality applications, but some incorporate a substantial degree of force feedback. The most advanced device, the Cyber Force (pictured left below) is a whole hand and arm force feedback device. It provides gross force feedback to the arm, while an exoskeleton that fits over the hand provides individual finger force feedback to enable the user to “feel” and manipulate virtual objects.



Fig.21 haptic devices

## EXOSKELETON MASTERARM

The pictured exoskeleton, from the Korean Institute of Science and Technology is not, in fact an exoskeleton for force amplification, but rather a “master” haptic device designed for controlling teleoperated “slave” robotic arms. The device incorporates force feedback to the operator, which is implemented via a system of electric brakes.

The exoskeleton masterarm has been successfully used to teleoperate the upper limbs of a humanoid robot called CENTAUR [Kim99].

The brake implementation of force feedback is simple and relatively easy to implement, but has the limitation that only “resistive” forces can be reflected. That is, the operator will only feel forces which oppose the direction of motion of the arms, not a full range of active forces which might act on the robotic arms.

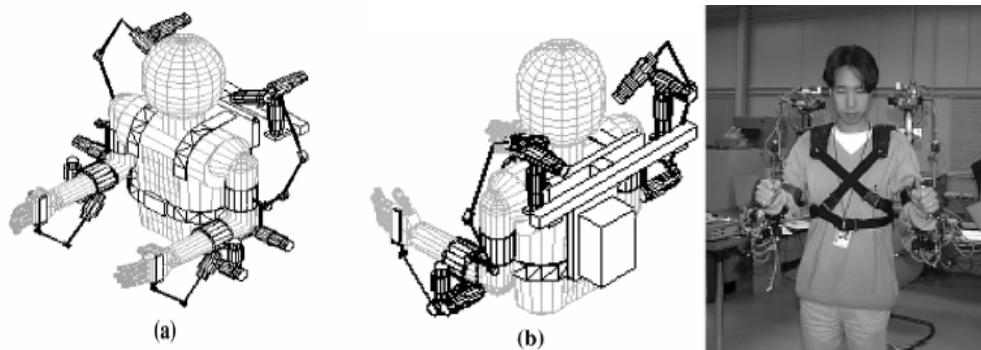


Fig.22 a “masterarm” haptic device

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## ACADEMIC RESEARCH IN THE COBOTICS AREA

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### IMAGINING THE FUTURE

Faulring [Faulring02] provides the following to describe the future potential of cobots

“The development of cobots with larger workspaces, powered actuators, and damping and stiffness schemes will provide numerous new capabilities to the implementation of cobot and haptic technologies. Automotive designers could test the operation of a virtual parking brake or shifter, walk around a full-scale virtual car, or lean under the hood to see if they can reach where the oil filter or spark plugs have been placed. As the designer tests the parking brake’s action, or removes the virtual oil filter, the objects on the end of the cobotic arm could be provided with the stiffness and friction characteristics being tested. Surgeons could plan a surgery by analysing offline MRI data or real time X-ray or fluoroscopy data to determine boundaries that surgical instruments should not penetrate. If the surgeon’s implement is fixed in a cobot, the cobot could keep the tool from penetrating vital organs while the surgeon still controls the allowed actions of the implement. Assembly workers will suffer less repetitive strain injuries as cobot guided material handling actions are made more ergonomic. Automotive components with large inertias could be constrained to a

small subset of six degrees of freedom, allowing workers to easily perform secondary tasks such as wiring and fastener installation. Numerous other uses in design, manufacturing, medical and entertainment applications will arise for the simple and safe cobot interface through advances in cobot capabilities”

Much research is required to overcome the current limitations of the cobot technology in order to realise these predictions. In particular, in the context of meat processing, the following issues need addressing.

- (1) A cobot with sufficient dexterity to handle, for example, a meat processing operation needs to be able to move in all six dimensions. Such higher degree-of-freedom cobots have significantly smaller workspace compared to traditional industrial robots. Cobots with large workspace such as the Pallet Jack cobot shown in Figure 3.4 have only three degrees-of-freedom.
- (2) Typical cobots are unable to amplify a human’s force. Cobots such as the Stanley rail-based cobot can only provide limited assistance. The absence of power to move links relative to one another is the main reason for this as current cobots can only steer links relative to one another.
- (3) Sensing ability of the current cobotic systems and the control strategies available for responding to the sensor measurements are very limited.
- (4) Current generation of cobots are unlikely to provide a sufficient speed of response to maintain current productivity.
- (5) Safety issues in the context where a common workspace is shared between a robot and a human may prevent the use of fast and active cobots for meat processing.

#### **KEY RESEARCH GROUPS**

There is significant research activity in the various aspects associated with robotics. The activities of the key research groups in cobotics and related areas are briefly described below.

- Laboratory for Intelligent Mechanical Systems (LIMS), Northwestern University.

The group led by Professors Colgate and Peshkin is arguably the world leaders in cobotics. They is perhaps the leading research group. This group coined the term “cobotics” and has been active in this area since 1996. The current research is focused on haptic devices, teleoperation and human interaction with passive robots, in particular for biomedical applications.

- Department of Mechanical engineering and Division of Bioengineering, National University of Singapore

This group is collaborating with the researchers at LIMS on cobotics. The focus is on the application of cobotics in wheelchair path and motion planning.

- College of Mechanical and Electrical Engineering, Harbin Engineering University, China

A research team at Harbin have developed a five-linkage serial cobot which uses two continuously variable transmissions (CVTs) connected in parallel mode. Design, and the trajectory planning and control of such robots is the research focus of this team.

In addition to the groups that focus directly on cobotics, there is a very large research community in robotics and related areas. There is a large community in haptics, in particular in relation to teleoperated surgical robots. Some attention has been given to sensing for capturing human actions. The research outcomes in this community should be useful in the red meat processing and cobotic systems. Similarly the output from the groups working on exoskeletons such as the Oak Ridge National Labs and University of California, Berkeley are likely to be of value.

Force control of robotics manipulators where the end-effector is required to exert prescribed forces on the environment has been an active area in the past. Much of the theoretical foundations in this area are now well understood. The robotics laboratories at Stanford University (Professor Ossama Khatib) and Catholic University of Leuven (Professor Joris De Shutter) have made major contributions to this area. Currently the Leuven group is collaborating with Toyota to develop a human-robot collaborative system to install windscreens on cars.

The Fraunhofer Institute at Stuttgart is another organization that is active in the area of robot assistants. The 2005 paper by Schraft et al [Schraft05] describes a robotic assistant for assembly tasks, and also contains a useful conceptual overview of robotic assistants. The team is led by Professor Rolf Dieter Schraft.

While the robotic community in Australia is large, there is comparatively small research activity in robotic manipulators. The CSIRO effort is well known to MLA. Professor James Trevelyan at University of WA did pioneering work on sheep shearing and Professor Malcolm Good at University of Melbourne was active in the force control area.

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## **PRACTICAL ISSUES FOR MEAT PROCESSING APPLICATIONS**

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The employment of cobots and IADs to assist workers in the meat industry is a very attractive prospect. A successful implementation could have a significant in reducing strain on the body, preventing injuries and extending the working life of meat workers. Cobotic assistance could also open up some physically intensive tasks to workers with a wider range of physiques.

The realistic application of cobots and IADs in the meat processing industry requires consideration of physical, logistical and economic constraints on their installation and operation.

### **DEGREES OF FREEDOM**

Most of the tasks in meat processing applications require full six degree of freedom manipulation of tools (three spatial and three orientation). Boning room tasks in particular are very complex and require rapid manipulation in six degrees of freedom.

Some tasks require fewer degrees of freedom, notably palletizing boxes, and hide removal. Hide removal is already a mechanized process in most meat rooms. Palletizing could benefit from some of the existing commercial lifter and rail systems such as the iLift or the G-Force.

It is significant to note that the existing commercial Cobot applications all have significantly fewer than six degrees of freedom. The lifters iLift and G-Force are principally one (position) degree of freedom, which can be extended to three with the addition of a (passive or active) rail system. Positioners such as the pallet-jack cobot and the door-unloader have two degrees of freedom (one position, one orientation), or sometimes three when a lifter is added.

Even prototype cobots seldom have a full six degrees of freedom. Research in haptics and teleoperation however indicates that cobotic devices with six degrees of freedom are possible. The main difficulty that faces designers of such devices is incorporating a six degree of freedom human input into a device at a position very close to the end-effector.

### **MOUNTING POINT**

An assistive device which provides force assistance must be mounted within the environment. The mounting point is required as a sink for reaction forces. For devices which provide very substantial forces (either assistive or passive), the mounting point needs to be a fixed point (on e.g the ceiling or floor). The requirement to mount the device at a fixed point places restrictions on the range of movement of the end-effector of the device.

For lower force applications, the mounting point may be on the operator – for instance an upper body exoskeleton may be mounted on the torso of the operator, with reaction forces supported through the hips. It should be noted that the forces provided in exoskeleton applications (and any other body-mounted application) must be low enough for the body to bear. This form of assistance is not redundant, as forces may be redirected from parts of the body with low force capacity (such as the lower arms) to parts of the body with high force capacity (such as the hips and legs).

### **SPEED OF RESPONSE**

If an assistive device is to be implemented in a commercial setting, it is important that there is no reduction in productivity on introduction of the device. In the case of meat processing (and boning room tasks in particular), movements are both complex and very rapid. Precise numerical data on the speed of operation is not available, but it is expected that translational and rotational speeds would be in excess of 1m/s and 360°/s respectively.

It would be necessary before embarking on a significant cobotic meat processing research project, to measure task speeds more precisely. This could be accomplished by instrumenting or filming workers while they perform candidate tasks.

### **FORCES REQUIRED OF MANIPULATORS**

The forces required in meat processing tasks would be a significant factor in developing any cobotic system, and also on evaluating the viability of various cobotic configurations. Again, numerical data is not available, but it is expected that some tasks would require in excess of 200N on a single arm. Numerical data could be gathered by the use of tools (knives, hooks etc) instrumented with strain gauges. The operators probably control the forces applied not only using the visual feedback and the knowledge of the operation but also through tactile feedback received during the process. Thus the control system used to generate forces need to be sensor-based feedback system.

### **SAFETY ISSUES**

Occupational health and safety regulations in the context of using robots and human in the same workspace also needs addressing. Colgate et. al. [Colgate 03] describes the draft standard that is being prepared by the Robot Industry Association in the US for cobotic applications. It is unlikely

that the guidelines currently being drawn will be applicable to active cobots that incorporate force amplification. German standard for sharing workspace between a human and a robot (DIN ISO 954) exists although the regulations severely limit the speed of the robot. Current guidelines suggest a maximum of 25 mm/sec when it is in the vicinity of the human operator.

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## SUMMARY AND RECOMMENDATIONS

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The development of robotic devices for direct interaction with human operators has been an active area of research over the past decade. A number of devices have been demonstrated, some practical and some illustrative. A few of these devices have been developed commercially, mainly in the area of material transport and positioning.

Related areas of research include robotic teleoperation, haptic interfaces and exoskeletons. These areas have been studied for a much longer period than cobotics, and can potentially make important technological contributions to the development of a cobotic application.

We believe that cobotics has potential in the long term to provide assistance to workers in the meat industry. Such assistance should result in increased safety levels, reduced injury rates and the ability to broaden the workforce in terms of the physique required to perform particular tasks.

Some of the cobotic devices described in this document (lifter and rail systems in particular) could potentially be applied in the palletizing of boxed meat products. Such tasks have been fully automated in other industries, although a specific cost-benefit analysis would need to be carried-out to evaluate the effectiveness of such a deployment.

Existing cobotics devices, either available commercially or as research prototypes do not have the essential capabilities to be directly used in the vast majority of meat processing tasks. The current research focus in cobotics is on improving the dexterity of a human operator and providing support for manipulating heavy objects and not on providing force amplification in multiple degrees-of-freedom. Although the theoretical foundations in this area are well understood, we did not find any research team in the world that is directly addressing this aspect of cobotics. Therefore, cobotics devices that are of direct use to meat processing are unlikely to emerge in the near future unless specific research and development activities are undertaken. A number of significant practical and technological issues need to be resolved before successful implementations of cobotics can be achieved in the boning rooms of Australian abattoirs.

- Existing force assistance applications generally have few degrees of freedom. Improvements are needed before cobotic devices can be implemented in the meat industry, where many tasks (particularly in the boning room) require the application of forces and torques in many directions. There are also practical issues in the application of high degree of freedom inputs to cobotic devices – this is an area where haptics research may be of benefit.
- Workers in the meat industry generally work with quite large forces and high speeds. It is very likely that further improvement of cobotic technology is required in order to facilitate the high speed and accelerations of effectors for the meat industry (and again, some boning tasks appear to be the most difficult). It would also be of significant interest to obtain numerical data (on forces, velocities and accelerations) for some key meat processing tasks.



- Safety will always be of paramount importance in the development of new technology for interaction with people. Safety considerations will have a significant impact when determining operating speeds and forces, mounting positions, and range of operation of cobotic devices. There will also be legislative considerations, which hopefully can be overcome if practical safe operating conditions can be achieved.

We feel that the next step in properly evaluating the future of cobotics and related technologies in the meat processing industry is to obtain numerical data on the forces and motions on some selected tasks from the abattoir. The tasks selected should include some which are the “easiest” in terms of speeds and degrees of freedom, and hence the most likely to be able to benefit from cobotics in the medium term. It would also be of value to obtain data on one or two of the most difficult tasks, in order to be able to evaluate the full range of force, velocity and acceleration involved. The industry will then be in a better position to judge the value of investing in a research and development program in cobotics. We also feel that this data will be valuable to the industry whether the future lies in cobotics, teleoperation, full automation, or elsewhere.

We would also encourage the meat industry to make contact with the leading researchers in cobotics and related technologies listed in this document. Those researchers may have a valuable input into broad questions of the viability of cobotic technology in meat processing, or may even have an interest in taking an active role.

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