# Robotic Processing of Variable Products

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## Abstract

This paper summarises research and commercial developments in robotics for handling and processing tasks involving a high degree of variability. The variability is often derived from the characteristics of individual items to be processed - e.g. natural product items such as meat portions or fish fillets which vary uniquely on an individual basis. Research into flexible knowledge-based programming, sensor measurement, and sensor feedback to accommodate task variability is described. Example developed systems include scaled wall framing construction for domestic buildings using expert knowledge on building techniques, palletising of variable-size oil canisters, automated de-boning of fish fillets, and robotic cutting of lamb carcasses. The projects described were all carried out by members of the Advanced Manufacturing Group at Industrial Research in New Zealand.

## 1. Introduction

This paper gives an overview of our research into robotics for handling and processing tasks involving a high degree of variability. The variability is derived from the characteristics of individual items to be processed, e.g. natural product items such as meat portions or fish fillets, or man-made items which are non-rigid or difficult to handle. Handling and processing tasks involving such variable items are typical of those found in New Zealand, where both the primary and secondary industries have products which present challenges to automation. Additional challenges are faced when small batch sizes of variable product items must be processed.

Industrial robotics has seen major technological developments in recent years following advances in information technology. Increased control processing speeds with servo cycles in excess of 1000 posture calculations per second and revolutionised drive technologies permitted the implementation of sophisticated control technologies. A comprehensive world-wide market for original equipment manufacturers (OEM) has emerged enabling specialised robotic developments. Overall, increased capabilities at declining costs allow the development of specialised machinery for applications in new and challenging areas.

Initially robotic applications in New Zealand followed world-wide trends in the car assembly industry and other related industries e.g. welding and single-product palletising. However, the bulk of potential robotic applications is in areas with high product item variability. These require specialised developments for robotic devices incorporating advanced sensing and processing capabilities. This is one of the reasons for the relatively late introduction of industrial robot technology to New Zealand. The following sections describe technique, research demonstrator projects and commercial systems that have been developed by the authors and their colleagues, which seek to overcome problems in dealing with variable products.

### Research activities

Our activities in robotics began more than 10 years ago. The emphasis in our research and development work is placed on flexible and adaptable systems particularly suitable for low batch production and variable products.
The following three categories of information processing for robotic systems have been implemented over the past years:

a) *Flexible programming:* An operator creates product or object information either off-line, interactively or on-line. This information is transmitted to the robotic machinery – no measurements are taken automatically.
b) *Sensor measurement*: Product or object information is measured automatically only once prior to the process. The operation is conducted without feedback.
c) *Sensor feedback:* Product or object information is measured continuously: the process operation is based on sensor measurements. One of the key aspects in this category is the processing of sensor signals, the ability to react on these measurements in real-time and to provide local intelligence to the machine.

The above techniques have been deployed in various demonstrations and commercial applications.

## 2. Flexible programming of robotic systems

In many manufacturing situations custom-made products are demanded. Knowledge-based design systems can significantly reduce both design time and robotic programming in such circumstances.

A prototype system developed by the team demonstrated the power of specialised graphical off-line programming. The purpose of the demonstrator was to investigate means of capturing and codifying rule-based design information, using it to verify individual product designs and then generate robotic path plans off-line for specific assembly operations.

An example application from the building sector was chosen. There are many rules that can be derived from the building code, and many process rules regarding best practice in building construction. In our initial 'building automation' project, the system carried out an assembly task for model scale wall framing for domestic buildings. The manipulator used was a gantry robot (Figure 1).

Each individual design is interactively derived, verified and corrected by elementary rules from the local building code. After completion of the wall design, the final frame layout is displayed on the screen by showing the resulting assembly sequence. After acceptance, the required parameters including wall dimension, stud spacing and the number of noggings, are down-loaded to the gantry controller. According to the screen design, the wall frame is laid out in a sequential pick and place operation. A new design can be entered during the operation, the same design can be repeated, or a previous design can be retrieved and down-loaded [Malone and Friedrich, 1990].

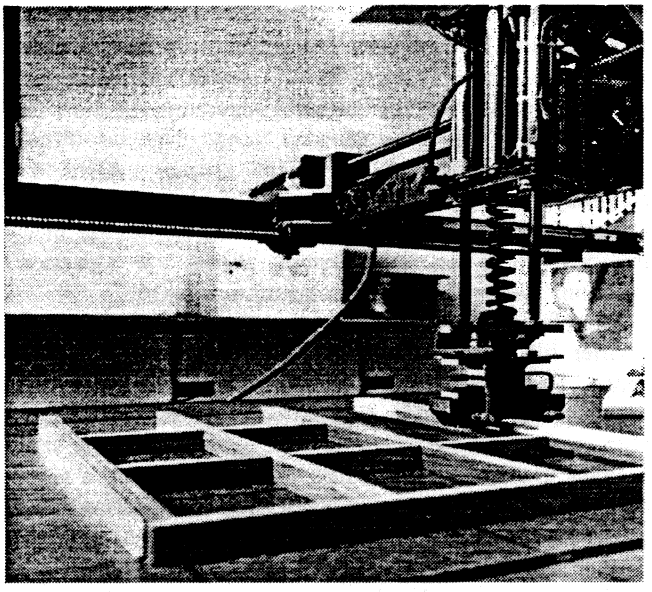

**Figure 1:** Building automation system.

Figure 1 shows part of the 2 ½ axis gantry part-way through a wall frame layout. The controller is based on a Baldor 2 axis motion controller. The third axis, the gripper rotation, and the gripper operation itself are powered pneumatically. Most of the robot movements are pre-programmed via a teach pendant, such as pick-up positions for stored pieces of timber as well as the bottom and side position for the first stud and bottom plate. Differing parameters for various wall designs eg. nog and stud spacing are down-loaded via a serial communication link from the graphical design station.

This design system is PC-based and programmed in Prolog. The operator replies to a series of questions concerning the position of the wall, for example whether the design will be used as an internal or an external wall, whether it is a load-bearing wall or not, etc. The rules from the knowledge-base suggest approved nogging requirements and stud spacing which the designer can accept or overwrite.

The pick and place operation for the wall assembly does not require any sensing prior to or during operation. The knowledge base is used to derive appropriate path plans off-line. In the next section, example applications provide sensor measurements either prior to the operation or during operation to adapt the process to individual object variations.

## 3. Self-adapting robotic systems

The challenge in processing of variable objects such as fruit, fish and meat lies in the capability to adapt each process to each individual object. Variable objects have similar generic characteristics but are intrinsically different in, for example, dimension, shape, texture and hardness. A successful system must therefore be able to accommodate this variability in objects by individually-tailored processing of each object. This can be accomplished by the use of sensory information concerning characteristics of each object to be processed, and modifying a generic task and path plan.

In principle, three major control modules are required: a sensing and perception module, a control module and an actuation module (Figure 2).

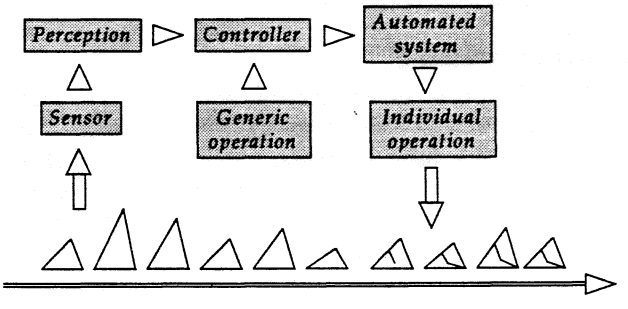


**Figure 2:** Advanced system approach for automated processing of variable products

The sensor-perception module processes raw sensor data using. sampling and filtering techniques. This module also combines data, interprets results and extracts significant information and acts as a perceiving mechanism. The relevant changes e.g. required path or position modifications are communicated to the control module.

From a generic operation containing the process description for the particular application, sensor-based adjustments are made. Depending on the nature of the application, the control module can generate commands such as a path for a robotic operation e.g. for cutting, or the commands for a handling operation [Kay et al., 1994].

In the actuation module, the control parameters and actuation requirements are converted into machine specific format, i.e. from geometric path information to motion commands, and transmitted to the actual controller. The key issue is the efficient and intelligent utilisation of sensor information to enable adaption to many individual product item variations.

The main use of sensors in such demanding applications is to increase system capabilities in two ways:

a) Firstly, by providing ***static*** data from the environment *prior* to the operation so that a plan of actions can be derived. Sensor information is processed prior to the robot operation. The subsequent process may not require any further sensing.
b) Secondly, by providing ***dynamic*** feedback data *continuously* during the operation e.g. to observe system status, to verify an expected event, to activate corrective actions, and also to monitor safety aspects and prevent any unexpected motions.

The effective use of appropriate sensor information is the key to extending system capabilities including self-correcting actions. The ability to retry and successfully complete automatically a failed handling action opens up new application areas. Likely applications for this technology are found in the processing of natural products including fish, meat, fruit, timber and pelts. This principle has been used to control, with the aid of sensing inputs, an end-effector for handling of variable flexible objects.

## 3.1 Applications with sensor measurement

### Commercial palletising

The above concepts of integrating sensory information closely to the control system were applied in a commercial system, which has been operating successfully for eight years. The task was to develop an automated system for the unloading and loading of oil containers from pallets for a major oil container. The palletising required programming a variety of palletising patterns, but the task was complicated by dimensional variations in the containers which could not be predicted fully in advance. A gantry robot was used to carry out the handling operations (Figure 3).

In the application, the large gantry robot unloads empty pails and loads full pails from the oil container filling station. The gantry spans over the size of two pallets, the first storing the empty containers, the second to be loaded with filled containers. The stacking pattern consists of a mixture of loading and unloading cycles to achieve optimised pallet loading times. The operator selects stacking height and one or both loading/unloading cycles. After the cycle the full pallet is transported automatically into the warehouse and the remaining pallet is moved forward and used as a loading base. The three main axes are based on AC motor technology, whilst the wrist and gripping action are pneumatically operated [Friedrich, 1995].

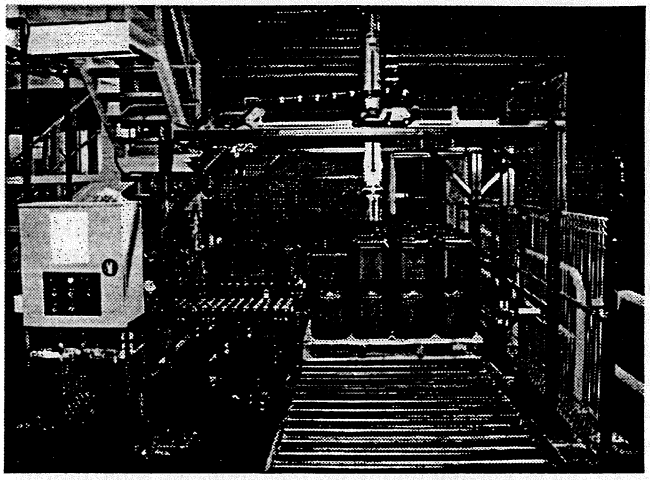

**Figure 3**: Commercial palletising system

The system controller consists of two parts, a robot controller and a PLC controller to interact with the warehouse and the operator. The robot controller is based on a stand-alone Baldor PMAC system providing all movement aspects of the handling operation as well as synchronisation with the conveyors to and from the filling station and monitoring all safety sensors. After an emergency stop, the operation can only resume with a key-operated switch for safety reasons. Similarly, in case of a misplaced container, the system allows for operator corrections and can resume the operation smoothly.

Significant variations in container dimensions before and after filling required additional sensing built into the gripper. These feedback signals are used to detect the container position within a predetermined distance range and to ensure that the container once gripped does not slip out again. However, should such a rare case occur, a self-correcting cycle attempts to recover from the situation. The system also provides operator messages such as system status, warnings and error messages on a LCD display.

The current cycle time amounts to approximately 8 seconds or 7 handling cycles per minute. The resulting pallet loading time is around 14 minutes.

## 3.2 Sensor feedback applications

The next generation of systems we developed provide sensor feedback at various level of complexity. These included the use of machine vision, tactile sensing and force sensing to enable the processing of variable product items, including natural products.

### Fish processing

Further development of intelligent automation took place via a proof-of-concept machine and then a commercial system for fish processing. The de-boning of fish fillets is a labour intensive, repetitive task with a high level of injuries. It is carried out in fish processing plants, and involves the human worker estimating the location of bones in the fish fillet and cutting out the flesh containing bones. It is a tedious task requiring complex eye-hand co-ordination, and the yield of the fillet is dependent upon the accuracy of the worker's estimates of where the bones are. It typifies the challenges of processing variable products: each fillet is 'the same but different', i.e. generic characteristics of the fillets can be defined, but each fillet will have geometric variations which make it uniquely different from all the others.

Our development of a 'fish de-boning' system (Figure 4) is based on three major components:

1) Sensing: a machine vision system that recognises lateral pin bones.
2) Control: the central control system designs a cutting path in real time, based on the outputs from the vision system.
3) Actuation & tooling: a two axis robotic manipulator guiding a waterjet cutter over a moving conveyor that transports the fish fillets to be processed.

Each of these systems provides specialised information processing capabilities. These components are integrated in a PC-based open architecture system consisting of special-purpose interfaces for machine vision and motion control.

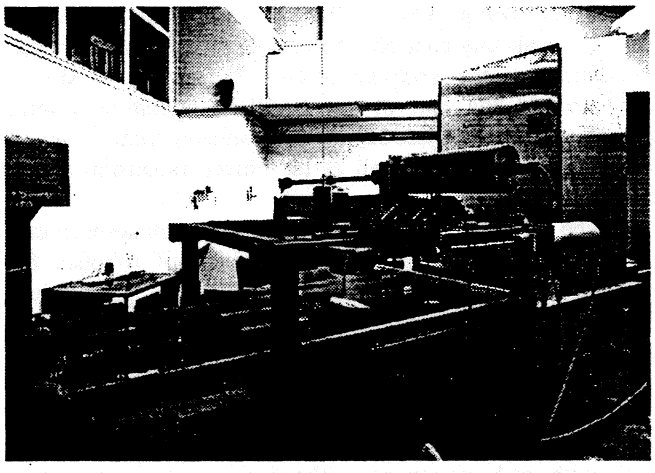

**Figure 4:** Fish de-boning system

In the proof-of-concept machine, Terakihi fillets were used. These have upward turning bones, called pin bones, whose end points are close to the surface of the fillet. The end points of the bones are usually visible under ultraviolet light. To detect the bones automatically, each fillet is passed through a shielded ultraviolet illumination chamber, and an image captured on a CCD camera. Initial image processing provides a series of potential bone positions, and also information regarding the location and geometry of the whole fillet.

However, some bone positions may not be visible, so the bone location data may be incomplete. In order to overcome this uncertainty, a rule-base was developed which defines the expected geometry of Terakihi fillets and bones. A matching operation is conducted on the data for a specific fillet, and the rule base used to complete any gaps or to resolve inconsistencies in the data from the vision system.

A cutting path around these pin bone locations is generated from the position data. The final cutting path is transferred to the motion controller, a Baldor PMAC system that operates the two axes gantry.

The cutting path is superimposed on the conveyor belt motion and performed by a water jet cutter mounted on the end of the gantry arm. For an acceptable cut quality cutting speeds of around 100 mm/sec are achievable. Cycle times were around 7 seconds but can be halved by processing fillets in a staggered fashion. The proposed sequence would allow image processing on the first fillet, while the second fillet is in transition and its cutting path is generated and a third fillet is being cut [Malone et al., 1994].

A commercial fish processing system, based on a similar approach was also developed. The task was the removal of the fat line in Hoki fillets, and similarly employed a machine vision system, a gantry robot, a conveyor and a waterjet cutter to carry out the operation. This machine operated in a New Zealand fish processing plant for several years.

### Meat processing

A major application area for our intelligent robotics activities is meat processing. Like fish processing, the meat-based product items such as lamb carcasses are all 'the same but different': generic properties can be determined but each individual product item (e.g. lamb carcass) will have its own unique characteristics. A further challenge is the harsh environment of the meat processing works: all equipment is hosed down each shift with high pressure hot water, and must be hygienic.

A series of robotic automation tasks for the removal of the pelt from lamb carcasses have been successfully achieved and trialled in operating meat works in New Zealand. One of the most trialled robotic tasks is the Y-cut operation. Y-cutting is a primary pelt removal task and involves cutting the pelt of a lamb carcass on both front legs [Taylor and Templer, 1997].

A manipulator was developed suitable for the challenging environment in meat processing plants. It is a 4 axis robot with a combination of linear and rotary axes driven by DC servo motors. The main linear axis of the robotic manipulator (Figure 5) is orientated horizontally and permits the robot to track the linear movement of each carcass as it travels suspended from an overhead conveyor. The arm can rotate vertically at the shoulder, extends 600mm and also has a wrist rotation. The load capacity is 7kg.

The specialised cutting tool uses an air-powered reciprocating knife to both cut and clear the pelt. Measurements using tactile sensors determine the animal size and leg position. The tool follows a pre-determined generic cutting path that is scaled for each individual object according to sensor measurements. The novel design of cutting blades is such that real-time force sensing is not required for the successful cutting operation.

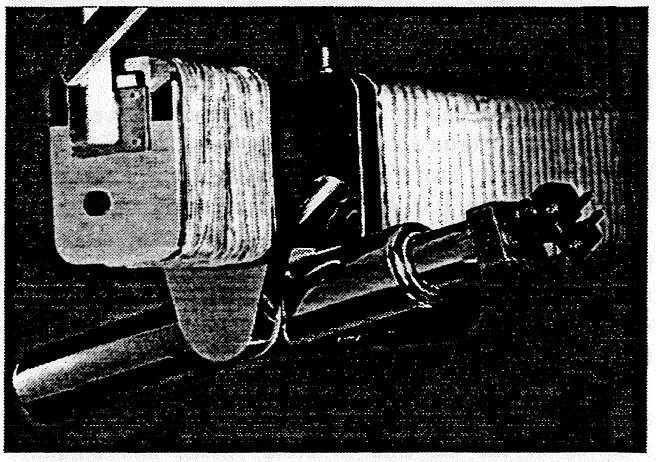

**Figure 5**: Y-cut robot system

Subsequent to the Y-cutting project, the manipulator and new tooling have been applied to other pelt removal tasks and trialled in operating plants. The manipulator has also been scaled up and modified for beef processing, and successfully used in a cutting operation in a Queensland beef plant. The manipulators and tooling have been commercialised with equipment manufacturers.

### Smart end effector

Our experiences of handling and processing variable products has led to the development of a modular gripping system with local intelligence. The end effector (Figure 6) provides a range of sensing capabilities and sensor-assisted motion control. It has a local controller which makes it independent of any manipulator, so that adjustments to gripping operations can be made locally in order to satisfy real-time constraints.

The gripper is instrumented with a range of tactile sensors for measuring the gripping force and the weight of the object, i.e. the resulting force from lifting the object is measured horizontally and vertically. Additionally, finger position and motion parameters are recorded. Control decisions are based on the combinations of various feedback signals [Friedrich, W.E., 1997].

The gripper system can distinguish various levels of hardness, as well as different levels of weight. Additionally, slip control is provided by monitoring tactile sensor outputs and adjusting applied forces, to avoid any possible damage to delicate objects. In order to lift the object a further increase of the gripping force is required. The resulting forces are recorded together with the finger positions. The relation of these measurements are the basis for estimating the hardness of the object. These results are used as the basis for applying an initial gripping force to lift the object.

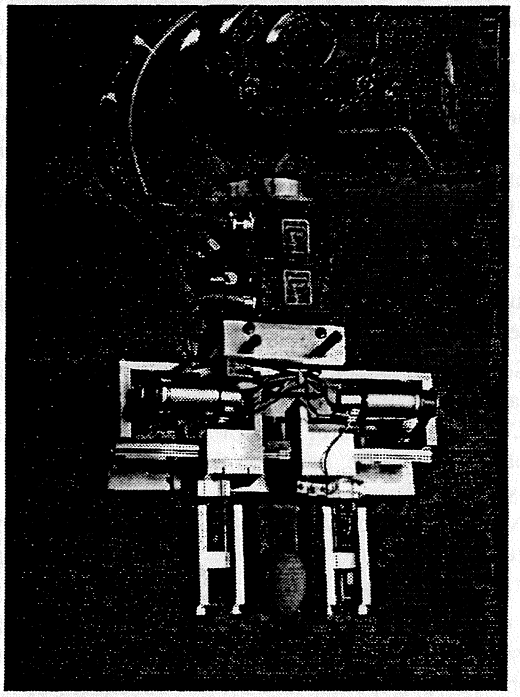

**Figure 6**: Smart end-effector

During the lifting of the object, the monitoring of vertical forces reveals any possible object slip. Slip can be corrected by increasing the gripping force until no further slip is detected. At the end of the handling operation several parameters of the object can be determined including weight and hardness levels as well as the object dimension across the line of gripping.

The close integration of sensing with actuation in end effector control is an important element of robotics for variable products. The inherent variability of the product items often places high demands on the sensory capability of automated equipment, and so we have adopted a modular approach with local intelligence in the end effector. This provides scope for smart end effectors to be mounted on simple manipulators, with the end effector being able to deal with task variations without recourse to a central controller.

## 4. Conclusion

The New Zealand environment presents many challenges for automated handling and processing. These challenges come from the fact that many applications require operations on product items that vary individually within a batch, often because the items were grown by nature rather than designed in a CAD system.

Our approach has been to develop systems that have strong sensory capability, and to integrate sensor data with versatile actuators, often in real time. We have demonstrated that knowledge-based systems can provide solutions in highly variable situations, for example in fish processing, and in off-line programming. Most of our research projects have led to commercial systems, and we have been able to transfer our results to equipment manufacturers and end users' engineers via trial programmes in operating plants.

Our current portfolio of projects covers further research into intelligent end effectors, semi-autonomous control for field applications, beef carcass processing, and two major systems for cutting and handling of lamb carcasses. All of these projects will have demanding sensory and control requirements, and will further develop the techniques described in this paper.

### ACKNOWLEDGEMENTS

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