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The concept and design of programmable array manipulator

Philip Ciufo
University of Wollongong, ciufo@uow.edu.au

Fazel Naghdy
University of Wollongong, fazel@uow.edu.au

Christopher D. Cook
University of Wollongong, chris_cook@uow.edu.au

Pak Chung Wong
University of Wollongong

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PROGRAMMABLE ARRAY MANIPULATOR, PART 2: The R & D Program

P. P. Ciufo†, F. Naghdy†, C. D. Cook†, P. C. Wong‡

†Department of Electrical and Computer Engineering

‡Apparel Robotics

University of Wollongong

Northfields Ave, Wollongong, N.S.W. 2522, AUSTRALIA

Phone : +61 42 213 065 Facsimile : +61 42 213 236

email:p.ciufo@uow.edu.au

Abstract: This paper is the complement to the Programmable Array Manipulator, Part 1. It presents an overview of the R & D program associated with the development of the PAM. The aspects of the control scheme are given as are some experimental results showing the preliminary capabilities of the PAM.

1. Introduction to R & D Program

This section of the paper describes work performed at the University of Wollongong associated with the development of the Programmable Array Manipulator. The concept of PAM is an entirely new idea. It involves the design and development of many new arrangements: both mechanical and electrical.

The project officially commenced in September 1990. The main thrust of work during the first 12 months concentrated on designing an actuator that could fulfil the requirements of PAM. This work has been reported by Laszlo *et. al.* in [1]. Following the successful design of a PAM actuation element, an entire PAM capable of manipulating objects was devised. More than one prototype was designed and built so that the optimum actuator could be found from those which had been proposed.

A prototype using 36 of the candidate actuators was constructed. The experimental work on this prototype provided some limited, but very useful results. Accordingly, a second, larger, PAM was designed so that further more applicable designs could be investigated. Such investigations were largely associated with the control and vision system for the PAM. The small 36 element PAM was not a realistic platform to test the control and vision algorithms devised for the manipulator, and so a 512 element array, arranged in a 32 by 16 manner was constructed.

This paper presents the work developed for the 36 and, to a lesser extent, the 512 element PAM's. The experimental results associated with translation and rotational performances are presented. Much work has been done on the control system for the PAM. The overall concept for this control and the results of some simulation work are described.

2. Modular Mechanical Design

In designing the a PAM, one of the requirements the research team had in mind was to maintain PAM as a modular device. The concept of PAM can be extended if one considers the device as more than just a machine for moving objects around. PAM can be made into a highly modular, reconfigurable device by organising the actuators into groups called Manipulation Modules (MM). For example, an MM could consist of an array of 32 by 16 actuators. It is then possible to design a PAM for a particular installation based on multiple MM's. Figure 1 demonstrates this concept.

The ability to rearrange MM's in a building block fashion has a number of advantages. For example, it allows a production line to be redesigned without the need to consider the location of the PAM extensively. Instead, the PAM can be reassembled to suit the application. The creation of MM's simplifies the process of PAM manufacture and provides cost benefits for both the manufacturer and the customer.

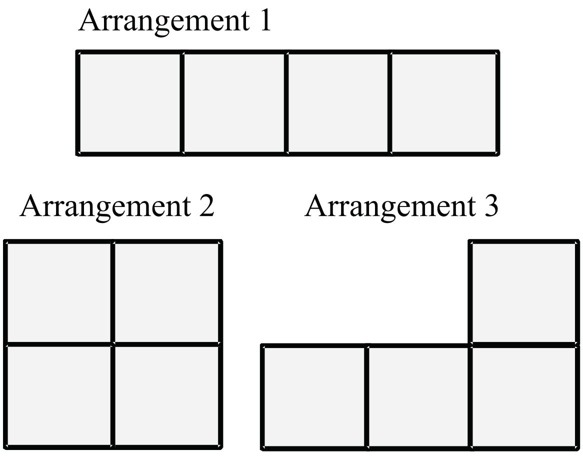

Figure 1 Possible MM Arrangements to form different PAM's.

3. Modular Control System

Two distinct features of the PAM are its inherent concurrency and modularity. The control system required for the PAM should obviously enhance these characteristics. This is particularly true in large systems where thousands of elements must operate in coordination with each other. The classic approach of using a central controller would present many problems.

Consider an area consisting of a 5 by 5 grid of work cells. At one end of the grid, the input side, a feed system delivers several differently coloured disks. Such an arrangement is shown in figure 2. The task is to organise these disks into a predefined pattern on a single work cell at the other end of the grid, the delivery side. At the delivery end of the grid, there is some other mechanism for removing the disk arrangement such that it is passed on to the next process. The disks are being delivered as a result of some other process upstream. The only control the grid has over this process is to stop and start it.

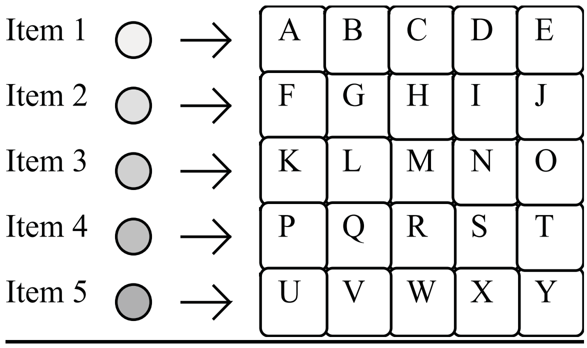

Figure 2 "Five by Five" Manipulation Module Arrangement

Suppose now that the 5 by 5 grid of work cells is to be extended, or mechanically reconfigured so that the number of objects required on the array rises to 8. It is obvious that a centralised control strategy suitable for the previous situation could not cope with this new situation and the rules of the control scheme should be re-authored. This is an expensive method of dealing with what is essentially a simple change. The inflexibility associated with the centralised approach reduces the effectiveness of PAM. It is possible to take into account every possible combination of operating conditions given a fixed mechanical arrangement, but it is, however, extremely difficult to compensate for every possible change in mechanical configuration. Any attempt to do this will be a waste of valuable computing resources.

Therefore the control scheme devised for PAM has a parallel structure in which the controller of each MM is loosely coupled with the other modules. The scheme has a hierarchical, multi-layered organisation. The layering is the result of the number of tasks required to be performed in parallel whilst controlling the PAM. The most difficult part of this structure is the control software that is responsible for the planning and coordination of the manipulated objects. The basis for this control operation is the demand-pull mechanism [3] commonly found in manufacturing automation.

The various layers of the devised control scheme, described by figure 3, are as follows:

1. Element Control Layer, or Actuator Control Layer
2. Object Control Layer,
3. Vision System Layer,

4. Command Layer, and
5. Communication Layer.

The layered approach of the control automatically introduces a structure in the program design which means that a review of certain aspects of the control scheme need not necessarily involve a rewrite of the entire code.

The task expected from each Module is determined by the information received from the neighbouring modules and *a priori* knowledge programmed into it according to the overall goal set for the PAM. This approach in the control scheme will not only simplify the overall design and development of the control system but also remains unchanged with the expansion or reduction of the PAM. Technical details of the implementation of such a control scheme for a working PAM is presented in [2].

Each layer has a set of responsibilities. The Element Control Layer is responsible for the interface between the Object Control Layer and the PAM elements. The Object Control Layer issues commands to the element layer in order to position and orient an object under its control. The Vision Layer provides position and orientation feedback for the Object Control Layer.

The Command Layer is arguably the most important layer within the control architecture. It is responsible for determining the tasks that PAM must perform. The command layer communicates its requirements with the surrounding control modules via the communication layer. Hence the Communication Layer is the gateway for the command layer into the surrounding processes.

3.1 Demand-Pull Mechanism

Demand pull is a method for a downstream process to get objects it requires from an upstream process. In a computer controlled environment, demand-pull is nothing more than a particular software strategy. For the PAM, this software fits into the Command Layer. In a manufacturing environment, demand-pull methodologies may result from the implementation of other control techniques, such as kanban.

To implement demand-pull, a control structure must be introduced that allows the effect to occur. The control structure devised allows the material to be pulled regardless of whether it is required immediately, or at a later time. It is assumed that the process being carried out by PAM is repetitive and continuous. Thus it will be performing the same task over and over again. The control structure is based on the role that an MM is capable of performing:

1. A *customer* manipulation module is an MM which requires an object. It wants this object in order to fulfil a task it is performing. This task could be initiated by a process external to PAM, or it could be as a result of another MM.
2. A *supplier* manipulation module is an MM which attempts to satisfy the demands of the customer MM.

Each type of MM can be further classified depending upon the location of the module with respect to the PAM overall task. These classifications are also based on the role of the MM:

1. A *target customer* is a manipulation module that terminates the PAM process. It is the MM that the objects being manipulated will finally arrive at prior to their removal and further processing on other machines.
2. A *primary supplier* is the first MM on the PAM to receive an object. Such an MM would have control over the process that supplies these objects. The supply mechanism in this case could be a conveyor, or a vibratory feeder.

In a large PAM, the roles of most suppliers and customers are interchangeable. In some instances an MM could be a customer, and at other times it could be a supplier. These dual roles are important, since it is the identity of the MM that determines what controls the pull mechanism. Each customer MM provides a control signal to the surrounding supplier MM's. Note that these surrounding supplier MM's are only classified as suppliers with respect to the customer MM. There is nothing stopping them from being classified as customers for their own purposes. This control signal is the desire to obtain a particular object at a given orientation. Such a desire is a result of the overall task that the PAM is performing. Such a task is delivered to PAM via the target customer(s).

In order to illustrate the pull mechanism further, consider the interchange between a customer MM and a supplier MM. Let the two MM's be defined as MM_a and MM_b, such that MM_a is the supplier and MM_b the customer. Each MM must keep a local record, or buffer, of the objects it has available and the items that it demands. As objects move onto a particular MM, they will appear in that MM's *input* buffer. As the objects move off the MM, the objects disappear from this buffer. A supplier PAM will also keep a record of requested objects. When a customer requests an object from a supplier, that request is stored in the supplier MM's *order* buffer. As the supplier provides this component to any customer, it disappears from this buffer. Observe that the supplier can supply the object to a different MM, rather than the one that placed the order initially.

The control pulse is provided by the customer MM. This control pulse takes the form of a message from one command layer to another. This message could be written as:

"please supply object X at orientation θ".

In this example, such a message would originate from MM_b and MM_a will respond with an affirmative or negative reply. If MM_a can satisfy the demand of MM_b it does so. If the reply is negative and MM_b cannot receive the item from anywhere else, then it must place an order for the object with the neighbouring supplier MM's. In the example there is only one MM that is able to provide objects to MM_b. In a real world example, MM_b could obtain items from up to four suppliers.

The order is then placed by MM_b with MM_a for an object. As far as the control scheme of MM_a is concerned, it has no memory of which MM wants this item. There is no memory of the owner of an order for a particular item. All that MM_a knows is that it requires an object, X. The net effect of this forgetful supply scheme is that the entire PAM will eventually have multiple objects being moved around towards the target customer. This ensures that the target MM will be able to obtain an item within a reasonable time.

Now that MM_a has an order to fulfil, it is no longer a supplier for the object it seeks. Since it is MM_a that wants the object in question, it must now behave as a customer in order to obtain it. The process is now repeated with MM_a acting as the source of the pull control pulse. Eventually, the pull control pulse will be satisfied when the object requested can be supplied without delay. The item can then back-track to the target customer.

3.3 Simulation of Command Layer.

In order to determine the behaviour of the PAM using the above control philosophy, a simulation was performed. There are a variety of behavioural properties that might be found if a complete simulation was written. There are, however, some aspects of the PAM control that cannot be simulated. Such aspects do not relate entirely to its control, but rather to the way the objects on a PAM behave. Collisions, jamming and so on are the sort of problems that this simulation cannot deal with.

The focus of the simulation is on the way that different manipulation modules interact whilst executing the demand-pull strategy. The simulation is based on a five by five square arrangement of manipulation modules as illustrated by figure 4. The MM's on the left most side of the PAM are primary suppliers of coloured disks. These disks are sized such that only five disks may be located on an MM at any one time. The supply of the disks onto these primary supply MM's can be applied in two ways: continuous flow of product, or a finite number of available disks.

The MM located in the right "lower" corner is the target customer. The aim of the exercise is to satisfy the demands of the target customer. It is programmed to array five disks, one of each colour into a predefined pattern. The arraying of the disks is not part of the simulation.

The simulation starts with the target customer requesting an object from its neighbours. The one limitation imposed on the control is that objects can only be supplied to an MM immediately from the left, below or above. An object cannot traverse a diagonal path when being passed from one MM to another. This is not a major deviation from impositions that may be set in place in the real world because an object crossing a diagonal boundary would require the coordination of the elements of four manipulation modules. The object would also find itself in a position where it is not really "owned" by one unique MM.

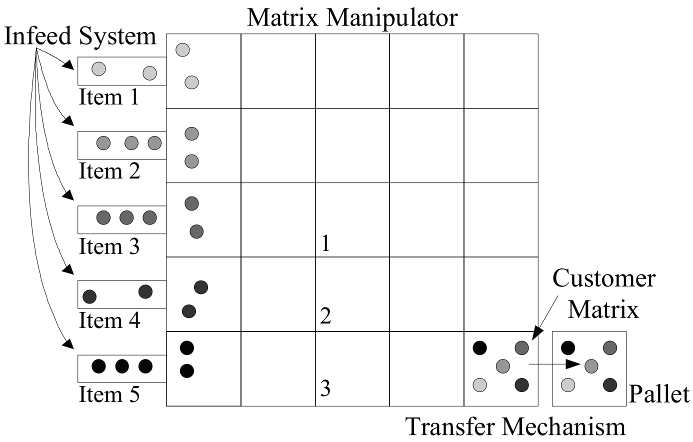

Figure 4 Simulation Scenario

One of the most important performance measures for the control strategy is the efficiency by which the objects are conveyed from one region of the PAM to another. There is a cost function which describes the minimum number of moves required by an object to traverse the PAM. In the simulation case, each object has a different minimum cost value since they start at different positions relative to the target array. Table 1 illustrates the various cost functions for the items in figure 4.

ITEM	COST FUNCTION
1	8
2	7
3	6
4	5
5	4

Table 1 Cost Functions

By observation of figure 4, the table is easily justified. For example, item 5 has to move 4 manipulation modules to the right in order to arrive at the target customer. The lowest cost value for the other objects are evaluated in the same way. The value of this parameter is a function of the task that the PAM is being asked to perform. If, for example, the target customer is located in the centre of the array then obviously the cost values would be different.

The types of issues under investigation in this simulation are:

1. The nature of the message passing between MM's.

2. Would it be possible to create a "traffic jam" of objects on the PAM ? If the demand-pull mechanisms try to route all of the items through a single MM, then the other units would not be used efficiently and one could reason that either the size of the array was incorrect, or the control scheme is not performing satisfactorily.

3. Would it be possible to have objects wander around aimlessly ?

4. Since the target customer is the master of the PAM, the way that the demands of this MM are propagated throughout the MM network needs to be established.

5. In this simulated example, there is a general flow of product from the left hand side of the PAM to the right hand side. Should product be allowed to move from right to left and should objects be allowed to backtrack over MM's that an object has already been through ?

6. Will the transfer of product from the primary suppliers to the target customer satisfy the cost function criteria ?

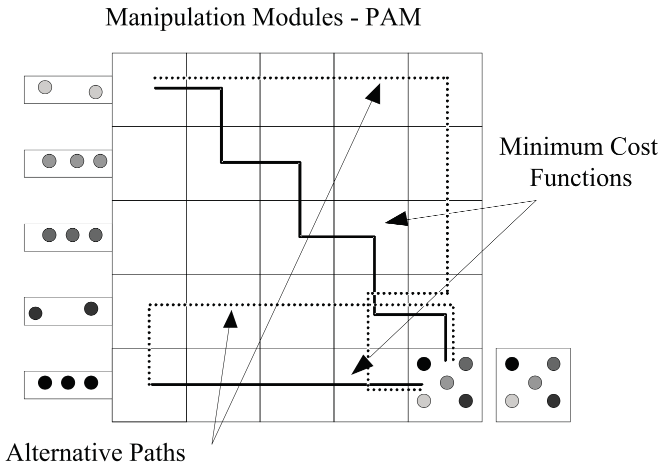

Figure 6 Alternative Cost Functions

As shown in figure 6, it is possible to have several cost functions for the same item. More than one minimum can occur just as more than one path of handling can occur.

7. In a real world application, it is possible that a complete MM could stop working due to a hardware failure. If this was to occur, in what way would the demand-pull mechanism be affected ?

8. In some cases, two Mm's could supply the same object. This situation should be prevented and mechanisms established to deal with this situation.

The results of inactive MM's, numbered 1, 2, & 3 in figure 5 are presented in table 2. The table does not present the resultant cost function for the case when no MM's are inactive, since the minimum cost function was met.

Item	No. of Inactive MM's	Cost Function	Actual Cost Function
1	1(MM 1)	7	8
2		6	7
3		5	6
4		6	5
5		7	6
1	2(MM 1 & 2)	8	8
2		7	7
3		6	6
4		7	7
5		8	8
1	3(MM 1, 2 & 3)	8	8
2		7	9
3		8	8
4		9	9
5		10	10

Table 2 Simulation Results - Including Multiple MM Failures

The results of this simulation indicate that the proposed demand-pull concept does operate efficiently. Each object was translated from its primary supplier to the target customer in the minimum number of movements. In the instances when one or more MM's are out of service, the cost function changes, with each item being delivered to the customer module without the cost function becoming excessive. In such an instance, it could be said that the demand-pull mechanism continues to work well.

4 Prototype Development

A great deal of effort has been placed on the process of designing an actuator that can manipulate objects on a PAM. The authors of [1] provide a list of various technologies suitable for such an application. As a result of the success of this actuator design, two prototypes were designed and built. The first prototype is an array of 36 actuators, occupying an area of 130 by 130 mm. This device was devised to determine experimentally the object velocities expected from PAM and the style of control required to rotate and translate an object. The second device is an array of 512 actuators occupying approximately 240 by 480 mm.

Much of the experimental work has been performed using the 36 element PAM. To date, only a limited amount of research has been performed using the 512 element unit. This has been a result of problems encountered in commissioning the device.

4.1 Prototype Control of Translation

In the experimental work associated with the control of object translation, several fundamental relationships were to be investigated. These were:

1. Translational velocity for various objects,
2. Repeatability of direction of translation for different object properties, and
3. Directional resolution.

The property (1) was investigated in order to determine the velocity performance one could expect from a multi-element PAM. Early simulation work based on a single actuation element model and prototype showed a conveying speed of 60 to 80 mm/sec was achievable.

The property (2) is important since if the PAM is to be capable of manipulating multiple objects, of different physical properties, then they should all respond in similar ways. If there was excessive variation in the object response, then more complex object identification techniques would be required. Alternatively, an adaptive control algorithm would need to be implemented. Such an algorithm could modify the look up table parameters for directional control based on the real time measurement of the object response on the PAM.

The property (3) would reveal whether or not the idea of directional control is successful. Without the angular resolution, the interface would need to be redesigned until an acceptable resolution was obtained.

The objects tested were:

1. an aluminium disk, 12 mm thick and 75 mm in diameter, and mass 223 g,
2. a steel disk, 15 mm thick, 75 mm diameter and mass 777 g,
3. a paper notepad, 75 mm square and mass 43 g, and
4. a roll of insulation tape, 65 mm diameter, 12 mm thick and mass 61 g.

4.2 Prototype Results of Velocity Trials

It was found experimentally that the mass of the objects had little effect on the speed of translation. The distance travelled was small since the array only allows approximately 60 mm of straight line travel. Since this distance is so short, there is no way of knowing whether the object would continue to accelerate had it been allowed to travel further. This did not appear to be the case; however the larger PAM will provide additional test results.

The tests performed indicate a speed of 30 to 40 mm/sec. There was a significant amount of uncertainty in this measurement due to the PAM itself. For example, the uneven surface of the 36 element prototype PAM meant that the object would not always travel in a straight line at a continuous speed. The object would often deviate around high areas of the PAM, or stall momentarily when a high spot was reached, however, the important factor demonstrated was the consistent velocity despite the variation in object parameters.

4.3 Prototype Directional Resolution

This experiment was performed to determine if the hardware designed for the control of the PAM was working as required. The design allowed for up to 32 different directions of translation. The following diagram demonstrates the phase versus direction characteristics using the Aluminium disk and the Steel disk as the objects. All directions are referenced to the direction obtained when controlling the actuators with direction 1 (of 32).

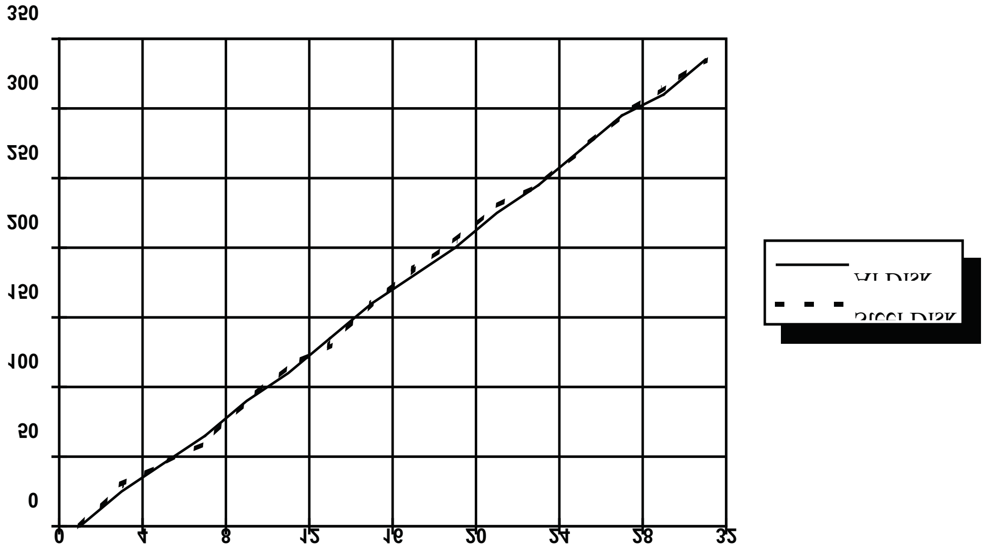

Figure 7 Direction of Translation Versus Phase

The test also determined that there was little effect on the direction of translation for different masses of object. This is observed by inspection of figure 7. The Aluminium disk and the Steel disk have considerably different masses. Despite this difference, the direction of translation versus phase characteristic are similar.

The task of rotating an object is considerably more difficult from that of translating an object. When a translation is being performed, then all the actuators under the object need to impart a force on the object in the same direction. In order to rotate an object a different strategy is required. Such strategies are shown in figure 8.

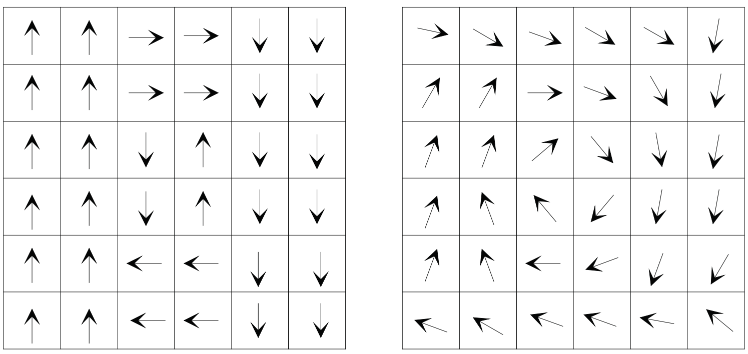

Figure 8 Rotation Strategies

Consider each arrow to be the force packet that the actuator can apply to the object that is resting upon it. These packets of force can be controlled by the Element Control layer. The technique at the right of figure 6 produces the most encouraging results. Table 3 lists the best clockwise and counter-clockwise rotation performances achieved by experimentation

Object	Best CW Performance	Best CCW Performance
Aluminium Disk	0.40	0.15
Steel Pulley	0.45	0.19
Paper Notepad	0.27	0.18
Insulation Tape	0.40	0.2

Table 3 Rotation Performances (revolutions per sec)

There is a principle that relates the number of elements in contact with the object with the ability to rotate the object. Prior to the experimental stage, it was known that there would be a connection with this ratio and the rotational performance. As a result of the experimental work, it has been determined that for flat based objects, the number of PAM elements required to rotate the object satisfactorily is of the order of 12 to 16. There does not appear to be this minimum number associated with the translational aspects of PAM. However, improved performance is achieved with more elements.

The second prototype is designed with 512 actuators arranged in a 32 by 16 matrix. The device occupies an area of approximately 240 by 480 mm. The actuators used for the second prototype are very different from those in the first. This is part of the process of design and refinement based on experimental research.

The actuators occupy about 60% less area than the ones used in the first version, so that a greater variety of objects may be tested for their suitability to rotation and translation. The second prototype is still undergoing commissioning at the time of writing this paper. Preliminary results indicate the translation speed of the object has been improved to approximately 60 mm/sec; however further work is required to substantiate this result.

5. Summary

The concept of the Programmable Array Manipulator as a new, innovative material handling device has been presented. The device has many unique features including a highly modular design which allows for quick reconfiguration both mechanically and from a control system point of view. Such a modular design, means that the device can be extended or reconfigured without the need for a totally new design of the control or the mechanical system. Such a device has many applications in the manufacturing sector.

In developing the PAM, a new method of transportation has been devised such that a single device can provide multi-directional feeding capability. This spin-off of the PAM design also has potential uses in industry. Two prototype PAM's have been designed and built, providing insight into the behaviour of objects on the PAM. Further research is being continued into the modelling of the device with the ultimate goal of using this model in the control of objects being manipulated by the PAM.

The vision component of the PAM is absolutely necessary if position and orientation control of an object on the PAM is required. The integration of a high speed system that can provide adequate processing speed performance whilst maintaining accuracy, is, in itself, a technical challenge. The system will need to eventually cope with multiple objects in initially unknown positions and possible problems with occlusion and object recognition.

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