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Robotic handling of nursery containers

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The Ohio State University, 1990
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ROBOTIC HANDLING OF NURSERY CONTAINERS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of the Ohio State University

By

Changhe Chen, B. Eng., M. S.

* * * * *

The Ohio State University

1990

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1.1 Application of Robots in Agriculture

This project was initiated with the objectives of developing conceptual models and constructing an experimental prototype of a multi-functional robotic system for the nursery industry. A conceptual system for the nursery industry was proposed by Chen at The Ohio State University (Chen, 1987). It is technically feasible for a robotic system with specially designed end-effectors to perform operations such as pruning plants, handling containers, precisely applying fertilizers and pesticides, harvesting and transplanting.

An agricultural robot must be rugged and able to survive the conditions currently experienced by agricultural machinery. Unfortunately, there are no general-purpose robots available for agricultural production and industrial robots are too expensive due to their high accuracy. Thus, developing a low cost, general-purpose agricultural robotic system is an objective of this research.

Although the first industrial robot was introduced in 1959 (Fu et al., 1987), it was not until the early 1980's that extensive research on agricultural robots was underway. The
First International Conference on Robotics and Intelligent Machines in Agriculture held in Gainesville, Florida in November 1983 was a milestone for agricultural robotic research. At this conference, research robots for orange harvesting, apple harvesting, tomato harvesting, and sheep shearing were presented.

A very interesting and complex robot application is the sheep shearing robot being developed by a group of scientists in Australia. The motivation for the project lies with the escalating labor rate for manual shearing. The robotic system consists of a sheep holding apparatus that restrains and immobilizes the sheep, a very high acceleration shearing head, and a complex sensing and motion control system (Field, 1982). Several types of sensing devices have been tested which include: contact resistance, capacitance and inductance sensing, ultrasonic distance measurement, sonic contact and force sensing (Trevelyan, 1984).

The use of robots to pick tree-fruit was first proposed by two California researchers in a 1968 review of mechanical citrus-harvesting systems. One of the concepts was the line of sight approach to fruit picking. An optical sensor is used to locate fruit and to guide the fruit detachment device along the line of sight to the fruit. The device is actuated when the fruit is contacted. It was not until 1984, however, that these technologies had been adequately developed for picking tree-fruit. Two years later in 1986, robotic picking research
was moved out of the laboratory and into the orchard for the first time (Grand d'Esnon et al., 1987). The sophisticated hydraulic robot developed by the French engineers was a self-propelled harvesting system which could automatically move down a row of apple trees, pick fruit, and convey them to a conventional harvesting bin. The system, called Maglie, operated for two months in 1986 and picked up to 50 per cent of the apples from the trees it harvested.

A similar mechanism called robotic grove-lab was developed at the University of Florida. This portable research facility is used to develop robotic citrus harvesting technology under actual production conditions. A color video camera is used as the optical sensor. The vision system can update the position of a targeted fruit 60 times a second to avoid unsuccessful pick cycles due to fruit motion. The end-effector used by the University of Florida researchers is a specially designed rotating-lip picking mechanism which is actuated with a double acting hydraulic cylinder. An ultrasonic transducer is also used to provide distance information to the objects in front of the picking mechanism (Harrell et al., 1988).

An intelligent agricultural robot which traveled between crop rows and harvested tomato fruit was developed and manufactured in the Laboratory of Agricultural Machinery of the Kyoto University. The robot, basically a battery powered car equipped with a manipulator and a color television camera
and controlled by an onboard microcomputer, is designed for general farm work. The sensory system recognizes the agricultural crop. In addition to harvesting tomatoes this robot was also adapted to transplanting and accurate pest control applications (Kawamura et al., 1986).

A cucumber sorting robot was developed by Mitsubishi Electric Corporation. It can sort cucumbers into nine categories by comparing the shape patterns obtained from a camera positioned above a sorting line with pre-defined patterns programmed into the computer. A separate microprocessor-based drop-out (sorting) control unit performs the sorting operation on the basis of the pattern signals (McClure, 1983).

At the University of California, Davis, a Rhino XR-1 robot and a computer vision system have been tested for the quality control check in egg production. Test results prove that the robotic egg candling system is both technically and economically feasible (Bourely et al., 1986).

A group of researchers at Purdue University successfully adapted an industrial robot, PUMA 560, to transplanting bedding plants. Different workcell configurations were studied. About 500 seedlings were transplanted at one time by the robot with a 96 per cent rate of success (Kutz, 1986).

A laboratory has been established at the Georgia Experiment Station which combines supervisory control, industrial robotics, and machine vision to study the
development of flexible automation systems for appropriate agricultural applications. Research is being focused on handling variability through system design and cultural practice, application of supervisory control, and use of specialized sensory systems. The commercial greenhouse industry has been targeted for the initial case study. A six degrees of freedom ASEA IRB 1000 robot and a Panasonic CCD camera are used together with the Heurikon computer to form the hardware for the study. Vegetative geranium propagation was selected as the first application for the laboratory (Simonton, 1988).

The milking robot that is currently being developed by French engineers consists of four manipulators (Mechineau et al., 1990). Each manipulator has six degrees of freedom, of which only three are motorized to reduce costs. Two arms are placed laterally and above the floor for the front teats. The other two are placed underneath the udder and below the floor level, reaching the rear teats through a trapdoor which opens as soon as the animal is in position. A specific stall with two gates on both ends is designed to confine the animal. Global and local sensors are used to locate the teats and to ensure a successful fitting of the teat cup.

Quite an effort has also been devoted to developing special end-effectors for agricultural purposes. The successful integration of a robot with any process requires an operational end-effector. At the New Jersey Agriculture
Experiment Station, a pneumatically actuated, positive action gripper equipped with a capacitive proximity sensor was being developed for seedling transplanting. The gripper is adaptable to a wide range of plug sizes and seedling shapes. The sensor on the gripper assures that the growing flats are transplanted with seedlings of satisfactory quality (Ting et al., 1988).

The most recent advances in robotics research in the agricultural industry were presented at the first workshop on Robotics in Agriculture and the Food Industry held in Avignon, France in June, 1990, by the International Advanced Robotics Programme (IARP). IARP is an international collaborative project initiated at the Versailles Economic Summit of 1982 with the general objective to foster international cooperation aiming to develop advanced robot systems able to dispense with human exposure to difficult activities in harsh, demanding or dangerous conditions or environments. During the workshop, researchers from all over the world made three dozen presentation ranging from general discussions to detail reports.

Lateral technology transfer was discussed by Arndt and Tedford (1990). The similarities of material handling and other operations between manufacturing industry and agricultural and food industry allow the latter to benefit through technology transfer. New applications of robots in the meat industry and horticulture were also discussed with
emphasis on meat grading, pelt removal, and fruit harvesting.

Nobutaka (1990) reported research achievements on agricultural robots in Japan. Yanmar developed a robotic transplanter which consists of a TV camera for collecting the image information and a fuzzy controller for steering. A fully automated combine harvester was developed with a plant row following system for guidance. A fertilizing robot was successfully developed by Mitsubishi to work in narrow spaces between rows of standing rice plants in the wet paddy field. Besides, a robotic lawn tractor and a driverless tractor were also developed.

Robot systems with computer vision capability were developed and tested to harvest, sort, grade, and pack produce in the agriculture and food industry (Sandini et al., 1990; Levi et al., 1990; Kassler, 1990). Besides sheep shearing and milking robot, animal robots such as the automated slaughter were being developed (Buhot et al., 1990).

Mobile robots begin to walk or roll into agricultural production. Walking machines were proposed for applications in the forestry industry because of the superior mobility and lower energy consumption of the legged systems over wheeled or tracked systems in most natural environments (Waldron et al., 1990). The fully self-contained six-legged Adaptive Suspension Vehicle was proposed as a good guide to those walking machines being developed for forestry applications.

From the above literature review it was concluded that
a robotic system might provide a solution for many labor intensive operations in the nursery industry, and the unloading/loading of nursery containers from a conveyor in a greenhouse environment was chosen as the first application.

1.2 Nursery Mechanization Now and in the Future
The highly labor intensive and seasonal nature of the nursery industry combined with increasing labor and material costs have made mechanization of various nursery/greenhouse operations increasingly attractive. Substantial work has been done to mechanize container handling (Spinks et al., 1980, Brown, 1976, and Jones, 1972) and other operations. The tasks have been difficult due to the nature of the work environment and the lack of standardization in materials and procedures.

Convenience is the major advantage of containerized nursery stock over conventional bedding plants. Ten years ago, containerized nursery plants made up over 23 percent of the $1.8 billion gross annual sales from wholesale nurseries in this country (Vanstone, 1979). Since then, container-grown nursery plants have been increasing steadily. The production of containerized nursery stock has expanded more rapidly than field-grown nursery plants not only because of consumer appeal, but also because of the production flexibility, and healthier, more uniform products it provides to the growers (Logan, 1982).
Given all the advantages of a containerized nursery stock why don't all nursery growers switch to containerized production? One major obstacle is the manual labor requirement for moving container-grown plants from one location to another. Logan (1982) cataloged container movement into five major areas, they are:

1) loading trailers at potting centers for transport to field,
2) unloading containers in field,
3) spacing containers midway through growing season,
4) loading containers in field for transport to shipping center, and
5) unloading containers at shipping center.

In a study conducted by Hahn et al. (1979) it was found that approximately 40 percent of the total costs involved in containerized nursery production was labor cost. With increasing labor cost it is expected to be higher today. Another study by Warneke and Perkins (1974) found that manual labor to move containers from one location to another accounted for one third of the total labor required to prepare plants for sale. For a large scale nursery operation productivity and unit rates are critical to its success since many thousands of plants must be moved in a short period of time.

Traditional mechanization methods have been developed over the years to help containerized nursery growers solve
some of their labor problems. Most of the current methods involve a trailer or a mobile platform that transports containers from one location to another. The major difference between these methods is the mechanism that loads or unloads the trailer or the mobile platform. Plants are loaded on the trailer in the central potting area and unloaded in the growing area. The current mechanization methods have not achieved the intended success because of the lack of flexibility and continuity.

With all current mechanization methods in place, one problem still remains unsolved. The problem is to quickly move the filled containers from the central potting station to the growing area.

Commercial robotic systems are available for greenhouse growers to move nursery containers from the central potting station to the growing area. The potting machine, the conveyor, and the robot arm are all in fixed positions inside the potting station. The belt conveyor has a fixed length and can only transport containers from the potting machine to the reach of the robot. Then the robot arm picks up the containers and spaces them on a large rectangular tray which slides horizontally beneath the conveyor and the robot. Each time the robot puts one row of containers on the tray, and the tray advances one row spacing. The continuous advancement of the tray makes it possible for the robot to fill up the tray with containers. Then the tray is pushed to the greenhouse
along the rails. At the same time the robot begins to put containers on another tray. Basically the greenhouse floor is covered with rails so that the trays can be positioned anywhere inside the greenhouse. The containers stay on the trays during the growing season. One major advantage of this system is that it can move large numbers of containers away from the central potting station in a short time period. However it involves very expensive trays and rails and also prevents the use of more efficient floor heating since plants are about 1 m above the floor (JAVO, 1987').

Another method that deserves special attention is the mechanism presented by Verma in 1981 to decentralize the potting operation. He proposed that the potting operation be performed in the field as the potting machine moved through the growing bed, rather than in a central potting area. Using this concept, soil and empty containers were transported to the field in bulk, as a result potting output was increased by a factor of almost ten.

Using the decentralized potting concept, the operation of a robotic nursery container handling system was proposed as in Figure 1. The potting machine moves along one side of the greenhouse. The extendable and retractable belt conveyor is fixed at one end to the potting machine and can transport containers all the way to the other side of the greenhouse.

'Mention of any product does not necessarily mean endorsement
Therefore the motion of the potting machine and the conveyor forms an X-Y table which can fill and convey containers to the entire greenhouse. As a result, the robot arm that is connected to the other end of the conveyor could place nursery containers anywhere inside the greenhouse as the conveyor extends or retracts. Most importantly, the robot system is capable of handling multiple nursery containers continuously, and thus it allows the nursery containers to be transported away from the potting machine at high speed and to be spaced directly on the greenhouse floor.
Figure 1. Conceptual sketch of a nursery robot system
CHAPTER II

OBJECTIVES

The goal of this research is to develop a fully mechanized robotic system for nursery container handling in greenhouses and nurseries. The objectives are:

1). Perform a computer graphics simulation of the MTS A-200 industrial robot to study the robot arm kinematics and to provide offline programming data for the robot.

2). Develop servo control for the MTS A-200 robot.

3). Develop PASCAL program on the HP 320 computer for supervisory control of the robot.

4). Test the MTS A-200 robot to validate the computer simulation results.

5). Simulate and design a simple and light weight 4 degrees of freedom cylindrical robot manipulator and its workcell.

6). Design and evaluate an extendable and retractable belt conveyor for the nursery robot system.
CHAPTER III
COMPUTER GRAPHICS SIMULATION

3.1 Introduction
In Webster's New English Dictionary, the word "simulate" means "to assume or have the mere appearance of, without the reality." This is the single most significant reason why simulation is such a powerful analysis method in science and engineering.

With the help of 3 dimensional (3D) computer graphics technology, robot operations can be simulated on computers even before the robot itself is constructed. In this way, engineers will have advance knowledge about whether their designs will or will not work for them and how the design can be modified to achieve their design objectives. Computer simulation thus can greatly reduce the time and work involved in the development of new robots. Once the robots are constructed the results from the computer simulation can be used to control the robots. This technique is called off-line programming and will be discussed in a later chapter.

Computer graphics simulation was done on an IBM4341 mainframe computer using a computer aided design (CAD) package called Computer-graphics Aided Three-dimensional Interactive
Application (CATIA\(^2\)). CATIA allows users to create objects in 3D space, and to visualize, manipulate, and analyze these objects. Most of all it is capable of solid modeling, and has specific modules for animating robotic type mechanisms to investigate system kinematics. From the result of the simulation, robot joint positions on the motion trajectory can be defined so that the coordination module can linearly interpolate between these positions to provide motion command to the joint servos. Also the simulation results provide the total time it takes the robot to perform one complete cycle of operation and thus computer simulations can optimize the robot workcell.

3.2 Simulation of the MTS A-200 robot

Shown in Figure 1 is the concept of the nursery robotic system. Nursery containers from the potting machine travel to the destination on the extendable and retractable conveyor. The container collector, the mechanism on top of the last section of the conveyor, holds the containers equal distance apart. The robot arm picks the containers up and swings to its sides and puts them down on the greenhouse floor. The robot is attached to one end of the conveyor and thus it will follow as the conveyor retracts or extends.

\(^2\)Product of Dassault Systems.
The capacity of the potting machine can be regulated between 600 to 6000 pots per hour. Once the operation speed of the robot has been determined the potting rate can be easily adjusted to match the handling rate of the robot.

For the purpose of simulation an existing industrial robot, MTS A-200, was used in place of the proposed robot. The MTS A-200 industrial robot is a hydraulically actuated, articulated robot, as shown in Figure 2. The configuration comes with four degrees of freedom (DOF) in waist, shoulder, elbow, and wrist roll. It has a very large load capacity of 90 kg even though that is not necessary for the container handling operation. The robot also has a large working envelope and heavy mass.

As the robot fills (or empties) a section of the greenhouse it will move progressively from one end of the bed to the other. Thus the conveyor handling the containers needs to be extendable and retractable. It should also be relatively light in weight yet strong enough to stand up under the abuse it will receive in the greenhouse environment.

In order for the robot to pick up multiple containers from the conveyor the containers must be correctly spaced on the conveyor. This is accomplished by the container collector shown in Figure 3. It consists of two rails that are parallel to the conveyor belt. Fingers are attached to both the rails. The last pair of fingers are fixed to the rails whereas the remaining fingers can rotate around their central pivot
points. The construction allows the operator to quickly adjust
the distance between the two rails and the pivot point on each
of the fingers to accommodate different sizes of containers.
When the conveyor belt moves one container through the
collector it can pass all the fingers except the last pair.
This is because the fingers rotate around their pivot points
when the container hits them. However the last pair of
Figure 3. Container collector
fingers will stop the first container. After the first container is in position it blocks the next pair of fingers so that they can not rotate around their pivot points. As a result, the second container is held in position. The chain reaction will allow the collector to hold all containers in place. A micro switch mechanism is used to detect the presence of the containers so that when all containers are in place the conveyor belt is stopped momentarily to allow the robot to unload the containers.

Figure 4 shows the fork shaped end effector that is used on the robot for picking up 15.24 cm (diameter) containers (3.785 liters in volume). A series of end effectors are available for containers of different sizes. The plastic container is of upside-down truncated conic shape and has a rim on the top. During the operation the end effector aligns with the containers first, then moves in and lifts up the containers by the rims. Both the container collector and the end effector are available in the market and were adapted for this application (JAVO, 1987).

Listed in Table 1 is the joint velocities of the MTS A-200 robot arm. Case I corresponds to the maximum joint velocities that the robot is designed to achieve. Case II is the actual joint velocities that were achieved during the lab test to ensure successful operation. More details about the slower velocities will be discussed in a later chapter.
Figure 4. Fork shaped robot end effector

Table 1. Joint Velocities of A-200 Robot Arm

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<tr>
<th>Joint Description</th>
<th>Maximum velocity degree/sec</th>
<th>Actual velocity degree/sec</th>
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<tr>
<td>joint 1 (waist)</td>
<td>120</td>
<td>91</td>
</tr>
<tr>
<td>joint 2 (shoulder)</td>
<td>23</td>
<td>17</td>
</tr>
<tr>
<td>joint 3 (elbow)</td>
<td>35</td>
<td>19.34</td>
</tr>
<tr>
<td>joint 4 (wrist roll)</td>
<td>180</td>
<td>113</td>
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Computer simulations were performed based on the two sets of robot joint velocities. It is necessary to ensure that the system accelerate smoothly at the beginning to increase velocity and decelerate smoothly at the end of the move. This is necessary to avoid exciting system vibrations (Waldron, 1984). For this purpose an ideal velocity profile shown in Figure 5 is suggested.

The term cycle time is often used as a single most important factor to study the performance of a robot arm. Cycle time is the time it takes the robot to finish one complete cycle of operation. For the container unloading operation the operation cycle begins when the robot hand positions on one side of the conveyor and aligns with the containers that are to be picked up from the conveyor. The robot arm then moves in and lifts up the containers. After that the robot arm moves to the destination and places the containers on the floor. The operation cycle ends when the robot arm moves back to the other side of the conveyor and aligns itself again with the containers. Two cycles of unloading operation with the MTS A-200 robot is displayed in Figure 6 (1st cycle: step 1 to step 8, 2nd cycle: step 8 to step 1).

The term upstroke/downstroke time stands for the time each joint of the robot arm accelerates/decelerates within one motion step. For fixed robot joint velocities, different upstroke or downstroke times gave different joint
accelerations, and thus resulted in different cycle times for
the robot operation.

Figure 5. Ideal robot operation profile
Simulation results of robot cycle times for the unloading operation were plotted in Figure 7. The results were expected since longer upstroke/downstroke times resulted in slower acceleration, and consequently longer cycle times. Also fast joint velocities resulted in shorter cycle times.

For the above simulation the robot puts containers on both sides of itself leaving a big aisle behind it, as shown...
Computer simulation of MTS robot

Figure 7. Operation cycle time for MTS robot
in Figure 8. Since greenhouse space is too valuable to waste the simulation was modified so that the robot arm put containers behind itself. In this way a very small aisle shown in Figure 9, or no aisle at all, can be achieved. On the other hand the robot arm needs to have an even larger working envelope and is going to have slightly larger cycle times. However for the MTS A-200 robot this modification is impossible since the maximum joint motion range for the waist joint is 240 degrees while the requirement for the same joint is more than 270 degrees. This is one design parameter that should be carefully considered for the new robot.

Figure 8. Big aisle with containers on the sides
3.3 Concept of new robot system

To make this system more practical a much lighter and simpler robot manipulator is needed. For simplicity cylindrical geometry is probably preferred rather than the articulated geometry of the A-200 robot. However 4 DOF is needed. Also for a general agricultural robot hydraulic actuation may be desired because of the general availability of the power source and the high force to weight ratio. However for greenhouse application an electric powered robot would probably be less expensive, and very satisfactory. To reduce
the structure weight both the conveyor and the robot arm will be built of aluminum. Figure 10 shows the proposed robot arm and its four joints.

Figure 10. Nursery robot and its joints
The proposed robot arm has great resemblance to the GMF A-1 robot arm. They have exactly the same cylindrical configuration and relatively close load capacity. However the nursery robot is going to be much lighter in structure and has a bigger joint motion range. Most importantly, the nursery robot does not need the high precision found in the GMF A-1 robot, therefore it should cost less to build. Nevertheless, the differences do not prevent us from using approximately the same joint velocities for the nursery robot. Table 2 lists the maximum joint velocities recommended for the nursery robot.

Table 2. Maximum Joint Velocity

<table>
<thead>
<tr>
<th>Joint</th>
<th>Joint velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 1</td>
<td>120° per sec.</td>
</tr>
<tr>
<td>Joint 2</td>
<td>0.61 m/sec.</td>
</tr>
<tr>
<td>Joint 3</td>
<td>1.22 m/sec.</td>
</tr>
<tr>
<td>Joint 4</td>
<td>120° per sec.</td>
</tr>
</tbody>
</table>

Robot arm trajectory for the container loading/unloading operation is directly associated with the relative position of the robot to the conveyor. For this reason, four workcells were specified based on possible layouts of the robot arm and the extendable belt conveyor, and are shown in Figure 11. All four workcells were simulated to determine the best work cell.
Figure 11. Workcell layouts of nursery robot
Computer simulations were performed for 4 different workcells using the same joint velocities and upstroke and downstroke times. The joint velocities used for the simulation were the maximum joint velocities listed in Table 2. The upstroke/downstroke time was assumed to be 0.4 second. The best workcell was chosen as the one with the shortest cycle time. All future simulation or design would be based on this workcell layout.

The cycle times listed in Table 3 were the time it took for the robot to place a row of containers on the floor (two sets of containers) instead of just one set. The reason for the modification is that three of the four workcells are not symmetrical and therefore the time it took the robot to place containers on the left or on the right was different. The actual operation cycle of the robot for each of the four workcells is displayed in Figure 12. Since the cycle times were so close together, the optimal workcell layout cannot be selected simply based on the cycle time only. Other factors such as the motion range of each robot joint should also be considered. This is the case for workcells 1 and 4. Workcell 1 requires joint 1 to have a minimum of 270° motion range while workcell 4 requires joint 3 to have a minimum motion range of 1.37 m. Larger joint motion range requires longer joint links and will most likely increase the complexity of the robot structure and thus the cost. Based on the above discussion workcell 3 was selected as the optimal layout for
the nursery robot system and will be used for subsequent simulation study. The minimum joint motion requirements of the nursery robot for all four workcells are listed in Table 4.

Table 3. Cycle Time for Different Workcells

<table>
<thead>
<tr>
<th>Workcell</th>
<th>Cycle Time, seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.8</td>
</tr>
<tr>
<td>2</td>
<td>15.3</td>
</tr>
<tr>
<td>3</td>
<td>15.2</td>
</tr>
<tr>
<td>4</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Table 4. Nursery Robot Joint Motion Range

<table>
<thead>
<tr>
<th>Joint</th>
<th>Cell 1</th>
<th>Cell 2</th>
<th>Cell 3</th>
<th>Cell 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>270°</td>
<td>135°</td>
<td>210°</td>
<td>90°</td>
</tr>
<tr>
<td>2</td>
<td>0.81 m</td>
<td>0.81 m</td>
<td>0.81 m</td>
<td>0.81 m</td>
</tr>
<tr>
<td>3</td>
<td>0.24 m</td>
<td>1.00 m</td>
<td>0.35 m</td>
<td>1.37 m</td>
</tr>
<tr>
<td>4</td>
<td>270°</td>
<td>225°</td>
<td>120°</td>
<td>180°</td>
</tr>
</tbody>
</table>
Figure 12. Operation cycles for all four workcells

(a) workcell 1

(b) workcell 2
Figure 12. (continued)

(c) workcell 3

(d) workcell 4
3.4 Optimal design of robot system

The process of designing the nursery robot is outlined by the flow chart of Figure 13. Assume here that we are going to build a greenhouse and select a completely automated robot system like the one that was proposed in the previous section to load/unload nursery containers. Where are we going to start? And what factors will be considered to have the right robot system. Those questions will be addressed in this section.

Robot kinematics is directly associated with the length of each link between robot joints. Therefore the first problem in designing a robot is to specify the length of each link. Three factors will contribute to the selection. They are conveyor height, greenhouse bed width, and work cell configuration. Conveyor height should be the same as that of the potting machine turn table unless the benefit of lowering the conveyor can be justified. Bed width is decided based on the biological effects and conveniences of operating other machinery inside the greenhouse. Work cell configuration should be designed in such a way that the robot operation is most efficient.

After the length of each link is successfully determined the robot trajectory, as well as the task, can be planned. The robot task, together with the specifications of the robot joint velocities and accelerations, would permit the robot cycle time for the specific operation to be determined.
Figure 13. Flow chart of designing the nursery robot
With the robot cycle time, the potting rate, and the container size, the number of containers the robot should handle each trip can be derived. That means the robot should handle the number of containers each trip to keep pace with the potting machine attached to the other end of the conveyor.

As the result of computer graphics simulation, workcell 3 was selected as the optimal arrangement which had a nearly 16 second cycle time for unloading two sets of containers. If the potting rate of one container per second is used, the robot arm should handle a minimum of eight containers at a time to keep pace with the potting machine.

Computer graphics simulation of workcell 3 also provided the link length for both the vertical and horizontal prismatic joints. The minimum link length for the vertical prismatic joint was found to be 0.8128 m and for the horizontal prismatic joint was found to be 1.016 m. The minimum joint motion range and the link length will be used in selecting components and in designing cross-sections for both links. Several steps of the simulation are displayed in Figure 14.
Figure 14. 3D simulation results
Figure 14. (continued)
Figure 14. (continued)
CHAPTER IV
ROBOT ARM DESIGN

4.1 Introduction
In the previous chapter a cylindrical geometry was chosen for the proposed robot arm. Because of the simple nature of most operations in greenhouse production, a robot arm with 4 degrees of freedom is adequate to perform the majority of operations required in a greenhouse or nursery. Computer graphics simulations were performed to optimize the robot workcells and to determine the operation cycle time. Robot joint motion requirements and the link length for both prismatic joints were also determined through those simulations. The 15.2 seconds cycle time suggested that eight containers should be handled each time by the robot to keep pace with the assumed one container per second potting rate.

4.2 Robot drive selection
Generally speaking, three types of actuation are available for driving a robot. They are electric, hydraulic and pneumatic. Actuation is selected on the basis of the characteristics of the specific application.
An electric system is clean and has an easily available power source. Moreover, an electric system allows the use of an accurate servo control. It is more convenient to manipulate the drive signal to produce a fast and stable robot motion. The disadvantage associated with the electric drive is that at certain speeds (usually, but not always, slow), mechanical resonances are excited and exceedingly rough motion results (a so-called "palsy" is exhibited). One of the primary causes of poor motion is the mechanical devices used to couple the motion of the actuator to the output of each joint mechanism. Nevertheless, despite the acknowledged difficulties with coupling devices such as a harmonic drive, the justification for this is that "torque multiplication" and increased position resolution that such components afford are absolutely critical in the successful design of robots (Klafter et al., 1989).

However in the early 1980s, a new motor was developed which does permit a practical direct-drive robot to be constructed. The motor, called a Megatorque motor, was manufactured by Motornetics Corporation. It can produce an extremely large torque at low angular velocities without the need for a speed reducer. The Megatorque motor is still very heavy in comparison to conventional motors and therefore has limited applications. Research efforts at both MIT and Carnegie-Mellon University are underway to develop additional commercial direct-drive motors (Klafter et al., 1989).
Hydraulic actuators are best known for their large torque or force output to weight ratio. This allows direct drive of the joints without any intervening transmission. Hydraulic actuators hold a fixed position well under load, thus, brakes are not needed. However they are less desirable at high joint rates and low loads because large amounts of energy are converted into heat at the control valves under these circumstances. The disadvantages of hydraulic systems are the need for a large, expensive and noisy power supply, the high cost of servo valves and the dirt engendered by oil leaks (Waldron, 1984).

Pneumatic systems are characterized by high speed and powerful operation with simple mechanisms. Moreover, owing to the compressibility of air, compliant motions can be realized if the air pressure is exactly controlled. Therefore, it seems that pneumatic actuators have many advantages. In practice, however, it is not easy to control the pneumatic drive systems. The reasons are summarized as follows: (1) Because of the dynamics of valves or the compressibility of air, the total dynamics of a pneumatic drive system can be described by a high order differential equation. Therefore, conventional PID (Proportional, Integral, and Differential) feedback controllers for positioning are not very effective because high order systems with more than third order lag can become unstable if unreasonable feedback gains are set. (2) The nonlinearity which comes from the
compressibility of air and friction dominates the motion of pneumatic drive systems. Therefore, to control the motion precisely, the nonlinearity must be considered (Kawamura et al., 1989).

Pneumatic drive robots do exist in industry. They are generally used for very light loads and simple configuration with less than four degrees of freedom. The most significant application of pneumatic drive robots is spray painting because oil leaks and electric sparks are not tolerable.

Based on the above discussion electric drive was selected for the proposed nursery robot. Four brushless DC motors are needed to drive the four robot joints. Since DC motors have high speed and low torque, speed reducers are necessary to couple the motors and the joints to reduce speed, and most importantly to increase the torque output.

4.3 Arm design
The nursery robot is controlled in an open loop manner with respect to the end effector position by sensing and feeding back only the four joint positions. Since elastic deflection of the structure creates a position error at the hand reference point, stiffness is the critical structural requirement for the robot arm, rather than strength.

Since strength is usually not a consideration, static deflection of the robot arm was used as the design criterion. For ease of manufacture and reduction in weight without
loosing stiffness, extruded square aluminum tube was selected for the robot arm.

The simplified robot model in Figure 15 is used for the selection of structural cross-sections. Because of both the low bending moments and the small cantilever length, the vertical rotational link and the end effector were modeled as being rigid and are combined with the pay load. All these were considered as being a point mass to be lumped at the outboard end of the horizontal prismatic link.

![Figure 15. Simplified robot arm model](image)
The worst case for static deflection occurs when both prismatic joints are fully extended. The horizontal displacement due to the bending of the vertical link can be reduced, and therefore neglected, by increasing the cross section of the vertical link without much penalty. Therefore the focus is only on the vertical displacement produced by bending both the vertical and horizontal links.

To establish the design criterion, a thorough analysis of the position error of the robot system is conducted below. Robot arm repeatability is the term used to determine the accuracy of the robot arm repeating its operations. Repeatability measures the position error of the robot end effector reference point between repetitions. As mentioned previously, the robot arm structure static deflection is one of the major contributions to the position error. Joint position feedback sensor resolution, control system error, backlashes of speed reducers, machining tolerance of mechanical parts, and robot joint alignment all contribute to the robot arm position error.

From observation of the lab test of the MTS A-200 robot arm, it was concluded that 6.35 mm maximum position error in both vertical and horizontal directions would allow the robot to function reasonably well.

If the total robot position error is distributed equally over the error caused by the structure static deflection and the error caused by the remaining factors, the maximum
structure static deflections in both horizontal and vertical directions are 3.18 mm.

The total static deflection in the horizontal direction is mainly caused by bending of the vertical prismatic link. The total static deflection in the vertical direction is caused by both the bending of the vertical prismatic link and the bending of the horizontal prismatic link. With relatively large length of the horizontal link the deflection angle caused by the bending of the vertical link tends to generate significant vertical deflection at the outboard end of the horizontal link. Since the horizontal deflection is quite small in comparison with the vertical deflection, vertical deflection will be used as the design criterion instead of horizontal deflection.

The criterion of determining the cross-section of the square aluminum tube is to maximize the stiffness to the structure weight by making the ratio of wall thickness to wall height as small as possible. However, if wall is too thin it becomes subject to local denting and, possibly buckling. A typical ratio of the wall thickness to wall height is, as used by Waldron (1984), 0.05. This number will be used in the determination of the robot link cross sections.

The variables used for the optimal selection of structural cross-sections are defined below.

$h_h$ --- cross-section height of horizontal link
$h_v$ --- cross-section height of vertical link
\( I_H \) --- area moment of inertia of cross-section of horizontal link

\( I_V \) --- area moment of inertia of cross-section of vertical link

\( E \) ---- Young's modulus

\( \rho \) ---- mass density

\( P \) ---- weight of actuators, end effector, and load lumped at the outboard end of horizontal link

\( W_H \) --- weight of horizontal link

\( W_V \) --- weight of vertical link

\( L_H \) --- length of horizontal link

\( L_V \) --- length of vertical link

\( n \) ---- non-dimensional constant defined by \( n = I_H / h_H^4 \)

\( c \) ---- non-dimensional constant defined by \( c = W_H / \rho g L_H h_H^2 \)

\( \phi \) ---- gradient at top of vertical link due to bending of the vertical link

\( \delta \) ---- vertical deflection at outboard end of horizontal link due to bending of horizontal link

\( y \) ---- total vertical deflection at outboard end of horizontal link

\( \lambda \) ---- non-dimensional ratio defined by \( \lambda = h_H / h_V \)

\[
\phi = \frac{(PL_H + W_H L_H/2)L_V}{EI_V} \quad (1)
\]

\[
\delta = \frac{W_H L_H^3}{8EI_H} + \frac{PL_H^3}{3EI_H} \quad (2)
\]
\[ y = \delta + fL_H \]  \hspace{1cm} (3)

\( P \) is the lumped weight at the outboard of the horizontal link. The popular 3.785 liter (one gallon) size containers used for the study weigh approximately 22.23 N with soil and plants. The end effector, together with the actuator and feedback sensor for the fourth joint weighs 66.68 N. Therefore the total weight \( P \) is 244.49 N.

For the square aluminum tube,
\[
E = 68,950 \text{ Mpa} \\
\rho = 2643 \text{ kg/m}^3 \\
[\sigma] = 186.17 \text{ Mpa} \\
P = 244.49 \text{ N} \\
L_H = 1.016 \text{ m} \\
L_H = 0.8128 \text{ m} \\
y = 3.18 \text{ mm}
\]

For the 0.05 optimal ratio of wall thickness to cross-section height, \( n \) and \( c \) can be easily found to be,
\[
n = 2.8658 \times 10^2 \\
c = 0.19
\]

Let \( \lambda = 0.6667 \) (Waldron, 1988), then
\[
I_Y = I_H/\lambda = 5.0625 I_H
\]

By substituting of all known parameters into equations (1), (2), and (3), equation (3) becomes,
\[
3.18 \times 10^3 = 3.3173 \times 10^7/h_H^2 + 4.3259 \times 10^5/h_H^4
\]
Equation (4) can be simplified into,

\[ 3.18 \times 10^5 h_H^2 - 54.1383 h_H - 6.3764 = 0 \] \hspace{1cm} (5)

Solving equation (5) for the real positive answer,

\[ h_H = 6.76 \times 10^2 \text{ m} \]

\[ = 67.60 \text{ mm} \]

\[ h_V = h_H / \lambda \]

\[ = 10.16 \times 10^2 \text{ m} \]

\[ = 101.60 \text{ mm} \]

For the 0.05 ratio of cross-section wall thickness to height, wall thickness for both links can be found as,

\[ t_H = 3.38 \text{ mm} \]

\[ t_V = 5.08 \text{ mm} \]

Finally, the weight of each link can be found as,

\[ W_H = 22.85 \text{ N} \]

\[ W_V = 41.29 \text{ N} \]

4.4 Electric drive component selection

Four brushless DC motors are needed to drive the four joints of the robot. Joint 1 and Joint 4 are both rotary joints, and therefore they only need pre-loaded gear trains to couple the motors and the joints. Pre-loading of the gear trains is necessary to reduce backlash. For each of the vertical and horizontal prismatic joints the drive mechanism consists of a DC servo motor that drives a precision ball screw through a timing-belt and pulleys. Anti-friction
bearings are used for all joints.

For position feedback, Linear Variable Differential Transformers (LVDTs) are used for the two prismatic joints and Rotary Variable Differential Transformers (RVDTs) are used for the two rotary joints. LVDTs and RVDTs are analog devices that would provide analog feedback of the joint position so that analog servo control can be easily achieved.

In this section the sizes of the motors and the speed reducers will be selected. Also the mechanical transmissions that convert the rotary motion of the motors into linear joint motion for the two prismatic joints will be selected.

For the waist, the joint velocity and acceleration are

\[
\omega_i = 120^\circ/\text{sec} \\
= 20 \text{ RPM} \\
\epsilon_i = 120^\circ/\text{sec}/0.4 \text{ sec} \\
= 5.24 \text{ rad/sec}^2
\]

Robot arm mass moment of inertia with respect to waist (neglecting the vertical link) is

\[
J_i = \frac{Pl^2}{g} + \frac{1}{3} \frac{W_n L_n^2}{g}
\]

(6)

\[
J_i = 244.49 \times 1.016^2/9.8 + \frac{1}{3} \times 22.85 \times 1.016^2/9.8 \\
= 26.57 \text{ Kgm}^2
\]

If damping and friction are neglected, the torque that is required to drive the waist can be found as

\[
T = J_i \epsilon_i \\
= 139.0 \text{ Nm}
\]

The DC motor runs at 1800 RPM, and therefore the gear
reduction for the speed reducer is

\[ n = \frac{1800}{20} = 90 \]

For the 90 gear reduction ratio a three stage gear train speed reducer is needed. Fortunately there is enough space for the waist joint to house the speed reducer. Assuming a 95% efficiency for each stage the total efficiency can be found as

\[ \eta = (95\%)^3 = 86\% \]

Therefore the motor stall torque is

\[ T_m = \frac{T}{n/\eta} = \frac{139.0}{90/86\%} = 1.80 \text{ Nm} \]

The following computation is performed to design the three stage gear trains (Machinery's Handbook, 23rd Edition, 1988, pp 1820).

Gear reduction for each stage:

\[ n_1 = n_2 = n_3 = n'' = 4.48 \]

Pressure angle: \( 20^\circ \)

Dedendum factor: \( K_v = 1.25 \)

Rack tooth filled radium: \( r_f = 7.62 \text{ mm} \)

Pinion torque:

\[ T_p = 1.80 \text{ Nm} \]
\[ T_{p2} = 7.66 \text{ Nm} \]
\[ T_{p3} = 32.60 \text{ Nm} \]

Load factor: \( K = 1.4 \)

Material hardness: \( H_v = 340 \text{ Bhn} \)
Material factor: \( K_m = 0.60 \)

Diametral pitch: \( p = 16 \)

Ratio factor:
\[
q = \frac{5}{90} + \frac{1}{(7 \, n_l^{0.3})} = 0.108
\]

Estimated number of teeth in pinion:
\[
\log N_p = \frac{1}{1 - q} \log \left( \frac{12.17 \, K_m \times 10^3}{H_b} \right) \tag{7}
\]

\[
\log N_p = 1.493
\]

\( N_p = 31 \)

Tooth number interpolation:
\[
i_N = \frac{40}{31} \left( \frac{31 - 30}{40 - 30} \right)
\]

\[
= 0.1290
\]

Gear ratio interpolation:
\[
i_m = \frac{10}{4.48} \left( \frac{4.48 - 3}{10 - 3} \right)
\]

\[
= 0.4719
\]

Geometry factor I and form factor J:
for \( n = 3 \), and \( N_p = 31 \)
\[
I_I = 0.1121 + i_N (0.1154 - 0.1121)
\]

\[
= 0.1125
\]

\[
J_I = 0.419 + i_N (0.452 - 0.419)
\]

\[
= 0.423
\]

for \( n = 10 \), and \( N_p = 31 \)
$I_2 = 0.1328 + i_N (0.1379 - 0.1328)$

$= 0.1335$

$J_2 = 0.432 + i_N (0.465 - 0.432)$

$= 0.436$

for $n = 4.48$, and $N_p = 31$

$I = 0.1125 + i_m (0.1335 - 0.1125)$

$= 0.1224$

$J = 0.423 + i_m (0.436 - 0.423)$

$= 0.429$

Allowable stress $S_r$ and $S_c$:

$\log S_r = \frac{3}{4} \log H_6 - 0.301 - \log K$ \hspace{1cm} (8)

$\log S_r = 1.4515$

$S_r = 28$ kpsi = 193.06 MPa

$S_c^2 = (S_H) K_m$ \hspace{1cm} (9)

$S_c^2 = 15870$ kpsi = 109423.65 MPa

Gear size and tooth number:

Stage I:

$F_D^2 = (10.58 T_n)/(I S_c^2)$ \hspace{1cm} (10)

$F_D^2 = 1422.91$ mm$^4$

$N_p = S_r F_D^2 J/(2T_n)$ \hspace{1cm} (11)

$N_p = 32.74 \quad --- \quad N_p = 33$

$N_s = n_t N_p = 146.66 \quad ------ \quad N_s = 147$

pinion and gear pitch diameters:

$D_p = N_p/p = 52.39$ mm

$D_s = N_s/p = 233.36$ mm

face width:
\[ F = \frac{FD_p^2}{D_p^2} = 0.52 \text{ mm} \]

**Stage II:**

\[ FD_p^2 = \frac{(10.58 \ T_p^2)}{(I S_i^2)} \]

\[ = 6055.27 \text{ mm}^2 \]

\[ N_p = S_i \frac{FD_p^2 J}{(2T_p)} \]

\[ = 32.74 \text{ ---- } N_p = 33 \]

\[ N_s = n_i \ N_p = 146.66 \text{ ---- } N_s = 147 \]

pinion and gear pitch diameters:

\[ D_p = \frac{N_p}{p} = 52.39 \text{ mm} \]

\[ D_s = \frac{N_s}{p} = 233.36 \text{ mm} \]

face width:

\[ F = \frac{FD_p^2}{D_p^2} = 2.21 \text{ mm} \]

**Stage III:**

\[ FD_p^2 = \frac{(10.58 \ T_p^2)}{(I S_i^2)} \]

\[ = 25786.29 \text{ mm}^2 \]

\[ N_p = S_i \frac{FD_p^2 J}{(2T_p)} \]

\[ = 32.74 \text{ ---- } N_p = 33 \]

\[ N_s = n_i \ N_p = 146.66 \text{ ---- } N_s = 147 \]

pinion and gear pitch diameters:

\[ D_p = \frac{N_p}{p} = 52.39 \text{ mm} \]

\[ D_s = \frac{N_s}{p} = 233.36 \text{ mm} \]

face width:

\[ F = \frac{FD_p^2}{D_p^2} = 9.42 \text{ mm} \]

The gear face widths found above were based on the safe stress. Actual face width can be larger. For simplicity, face width of 12.70 mm will be used for all three stages.
For the vertical prismatic joint, the linear velocity and acceleration are

\[ v = 0.61 \text{ m/sec} \]
\[ a = \frac{v}{0.4} \text{ sec} \]
\[ = 1.53 \text{ m/sec}^2 \]

The mass that the joint has to move is

\[ m = \frac{P + W_h}{g} \]
\[ = 31.49 \text{ Kg} \]

If damping and friction can be neglected, the force that is required to drive this joint can be found as

\[ F = ma \]
\[ = 48.18 \text{ N} \]

The DC motor drives the joint through a ball screw which has high mechanical efficiency and can be easily spring loaded to eliminate backlash by using a pre-loaded double nut. Comparatively speaking, ball screw drives are very stiff (Waldron, 1988).

Another ball screw is needed for the horizontal prismatic joint. The linear velocity and acceleration of this joint is

\[ v = 1.22 \text{ m/sec} \]
\[ a = \frac{v}{0.4} \text{ sec} \]
\[ = 3.05 \text{ m/sec}^2 \]

The mass that the joint has to move is

\[ m = \frac{P + W_h}{g} \]
\[ = 27.28 \text{ Kg} \]

Therefore the force that is required to drive this joint
is (neglecting the damping and friction)

\[ F = ma \]

\[ = 83.20 \text{ N} \]

For the wrist (joint 4), the joint velocity and acceleration are

\[ \omega_4 = 120^\circ/\text{sec} = 20 \text{ RPM} \]

\[ \varepsilon_4 = \omega_4/0.4 \text{ sec} = 5.23 \text{ rad/sec}^2 \]

The distance between two containers on the end effector is 0.20 m, so 8 containers spread to a total length of 1.6 m. Therefore the mass moment of inertia for the wrist can be found as

\[ J_4 = 1/12 \times 244.49/9.8 \times 1.6^2 \]

\[ = 5.32 \text{ Kgm}^2 \]

Hence if the damping and friction can be neglected the torque that is required to drive the wrist is

\[ T_4 = J_4 \varepsilon_4 \]

\[ = 27.82 \text{ Nm} \]

The DC motor rotates at 1800 RPM. To get the 20 RPM wrist motion a gear reduction of 90 is needed. However for the wrist, there is not enough space to house a gear train speed reducer. A harmonic drive is selected for the wrist joint because of its light weight, compactness, backlash free operation, and most of all the large speed reduction capability in a single stage. Disadvantages are modest mechanical efficiency (70%) and relatively high compliance (Waldron, 1988).
The motor torque requirement is

\[ T_m = \frac{T}{n/\eta} \]

\[ = 0.44 \text{ Nm} \]

4.5 Robot arm dynamic analysis

Even though structural static deflections were used as the design criteria for the selection of the robot arm cross-section dimensions, dynamic behavior of the robot arm cannot be neglected. Robot arm vibrations do not contribute to the steady state position error at the end effector reference point. However, for low structural natural frequencies, the vibratory behavior can severely affect the positioning of the robot joints, and therefore, the performance of the robot system. On the other hand, robot arm structural natural frequencies can not be in the same range as the servo control bandwidths or sampling rate, otherwise the system would develop the so called resonance, that is unstable, or oscillatory behavior. This vibration can be destructive in nature and should be avoided. To prevent resonance, any analog components in the servo loop must have bandwidths greater than the link structural frequency by a factor of at least 10. Those parts of the servo loop implemented as a sampled data system should have a sampling rate of at least 10 times the link structural frequency (Paul, 1981).

Dynamic analysis of the robot arm is to determine the vibration modes and to estimate the lowest natural frequency
for each of the vibration modes.

The simplified model of the nursery robot shown in Figure 11 may also serve the purpose for the dynamic analysis. The worst case for all vibration modes is when both prismatic joints are fully extended. Both member and joint compliance will be considered in estimating the lowest natural frequencies.

For the waist rotation (joint 1) the vibratory mode is the torsion around the joint. It is caused by the joint compliance and the torsional compliance of the vertical link. The torsional stiffness of the vertical link can be calculated as follows (Baumeister et al., 1987):

\[ k_r = \frac{h_r' G}{7.2 L_r} + \frac{(h_r - 2t_r)' G}{7.2 L_r} \] (12)

where \( G = 26201 \text{ MPa} \) is the shearing modulus for aluminum.

\[ k_r = 1.64 \times 10^7 \text{ Nm} \]

For purposes of estimating system lowest natural frequencies, the stiffness of a gear pair with respect to rotation of the output gear can be adequately approximated (Waldron, 1988) by

\[ k = C b r^2 \] (13)

where \( C = 13,400 \text{ MPa} \) is a constant,

\( b = \text{face width of the gears, and} \)

\( r = \text{radius of the output gear.} \)

Therefore for all three stages of gear pairs,

\[ k_1 = k_2 = k_3 = 13400 \times 10^6 \times 12.7 \times 116.68^2 \times 10^6 \]
= 2.32 x 10^6 Nm.

The total stiffness for the waist K is, therefore,

\[
\frac{1}{K} = \frac{1}{k_\nu} + \frac{1}{k_\gamma} + \frac{1}{n_3^2}\left[\frac{1}{k_3} + \frac{1}{(n_3^2 k_3)}\right]
\]  

(14)

\[
K = 1.53 \times 10^3 \text{ Nm}
\]

From the previous section, it was found that

\[
J_\gamma = 26.57 \text{ Kgm}^2
\]

Hence the natural frequency is

\[
\omega_1 = \left[\frac{K}{J_\gamma}\right]^{1/2}
\]  

(15)

\[
\omega_1 = 75.80 \text{ rad/sec}
\]

= 12 Hz

There are two vibratory modes for the vertical prismatic joint. One is the reciprocating motion along the joint. The other mode is the bending of the horizontal link. The reciprocating motion is caused by the actuator compliance of the second joint, while the bending mode is caused by the compliance of the horizontal link. The ball screw drive for the prismatic joint has very high stiffness (Waldron, 1988) and therefore the reciprocating motion along the joint has much higher natural frequency than the bending of the horizontal link. Hence only the natural frequency of the bending mode will be derived.

Stiffness of the horizontal link:

\[
K = 3 \frac{EI_h}{I_{gh}}
\]  

(16)

\[
K = 1.18 \times 10^5 \text{ N/m}
\]

Natural frequency for the bending mode is:

\[
\omega_2 = \left[\frac{Kg}{P}\right]^{1/2}
\]
= 68.78 Hz

The only vibratory mode for the horizontal prismatic link is the reciprocating motion along the joint. It is caused by the actuator compliance. Since the joint stiffness of the ball screw drive is comparatively very high, the natural frequency will be high enough not to cause any problem.

Both static load and dynamic load will be considered to study the maximum stress that is applied to the critical cross sections of the two links.

For the vertical link, both the shearing stress due to the torsion and the bending stress will be considered.

Shearing stress:

Maximum moment: \( M_s = J_i \epsilon_1 = 139.0 \text{ Nm} \)

Polar moment of inertia (Nash, 1972):
\[
J = \frac{t h^3}{12}
\]
\[
J = 5.3278 \times 10^6 \text{ m}^4
\]

Stress: \( \sigma_s = M_s \times 0.707 \frac{h_r}{J} \) (18)
\[
\sigma_s = 1.86 \text{ MPa}
\]

Bending stress:

Maximum moment: \( M_b = [P/g + W_h/(2g)](a_2 + g)h_r \)
\[+ (P/g + W_h/g)a_3h_r \]
\[
M_b = 368.25 \text{ Nm}
\]

Stress: \( \sigma_b = M_b/I_r \times h_r/2 \) (20)
\[
\sigma_b = 6.13 \text{ MPa}
\]
For the horizontal link, the critical cross section is at the place where horizontal link attaches to the vertical link. Only the bending stress will be considered.

Maximum bending moment:

\[ M = \left[ \frac{P}{g} + \frac{W_h}{(2g)} \right] (a_v + g)I_h \]

\[ M = 300.62 \text{ Nm} \]

Bending stress:

\[ \sigma = \frac{M}{I_h} \times \frac{h_h}{2} \]

\[ = 16.98 \text{ MPa} \]

The stresses found above are very small. Therefore the arm structure is safe.
5.1 Introduction
The coordination module is responsible for generating the position commands which are passed to the joint servos to generate smooth motions. While robot tasks may be described in terms of cartesian coordinates or in joint coordinates, robots are more simply moved in joint coordinates. Given two positions close together in space, a coordinated motion in joint coordinates from one position to the next is a differential approximation to a true straight line cartesian motion. Over large distances coordinated motion in joint coordinates is as predictable as straight cartesian motion. The computations necessary to move a robot in joint coordinates are only those necessary to provide for the coordination of the joints (Paul et al., 1979).

For the task of handling containers in a greenhouse a complicated trajectory is not necessary since conveyor tracking is not needed. The container collector on top of the last section of the conveyor keeps the containers in a fixed position and ready to be picked up by the robot arm. Only a few critical points need to be defined to ensure the
completion of the task. Between the pre-defined points linear interpolation in joint coordinates will be able to command the joint servos to generate smooth motions.

Conventional manipulator control systems are designed in such a way that the manipulator stops at the end of each path segment. For motions made up from a number of path segments this results in an inefficient operation. By eliminating the need to stop at the end of each path segment and by ensuring that the manipulator moves at maximum velocity and acceleration, the traveling time can be reduced (Paul et al., 1979).

Joint servo control is accomplished inside the Daytronic 10K1 DataPAC. Each joint of the robot arm is controlled by one Model 10APID Loop Control Card inside the DataPAC. Optimum weighting of the P, I, and D factors can produce a critically damped error signal. PID control was simulated using CSMP (Continuous System Modeling Program) to assist the determination of the P, I, and D factors. A block diagram of robot control is shown in Figure 16.

An HP 320 computer is used to provide supervisory control. The coordination module is furnished on the computer to pass motion commands to the joint servos in the DataPAC. Also the computer provides indexing information to the conveyor retract/extension mechanism.
Since the nursery robot has not yet been constructed, the control system was initially used to control the MTS A-200 robot. Lab tests on the MTS A-200 robot were conducted to validate the simulations previously done on the same system. Kinematic analysis on the MTS A-200 robot was also performed for programming the robot.
5.2. Denavit-Hartenberg parameters of MTS A-200

Figure 17 illustrates the kinematics of the MTS A-200 robot arm. Joint parameters were determined by using Denavit-Hartenberg convention (Fu et al., 1987) and were listed in Table 5. Please note that the actual robot arm used in this project was a 4 DOF model and link 4 was kept in vertical position by a series of linkages. Therefore the forth joint was not treated as a real joint, that is, the fourth joint does not contribute to the degree of freedom of the robot. And hence joint 4 is actually the fifth joint.

![Figure 17. Denavit-Hartenberg parameters of MTS A-200 robot arm](image-url)
Table 5. MTS A-200 robot D-H parameters

<table>
<thead>
<tr>
<th>Joint</th>
<th>$\theta$</th>
<th>$\alpha$</th>
<th>$a$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\theta_1$</td>
<td>-90°</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>$\theta_2$</td>
<td>0°</td>
<td>L</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>$\theta_3$</td>
<td>0°</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$\theta_4$</td>
<td>0°</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Robot arm home position was selected as the position with $\theta_1 = 0°$, $\theta_2 = 105°$, $\theta_3 = -90°$, and $\theta_4 = 0°$. These numbers were used in the inverse kinematics programs.

5.3 Inverse kinematics of the MTS A-200 robot

XYZ is the universal reference frame and xyz is the end effector reference frame.

Homogeneous transform matrix:

$$X = T_e = \text{Trans}[x_{14}, x_{24}, x_{34}] \text{Rot}(Z, \theta)$$

$$\begin{bmatrix}
x_{11} & x_{12} & x_{13} & x_{14} \\
x_{21} & x_{22} & x_{23} & x_{24} \\
x_{31} & x_{32} & x_{33} & x_{34} \\
x_{41} & x_{42} & x_{43} & x_{44}
\end{bmatrix} \begin{bmatrix}
\cos \theta & -\sin \theta & 0 & x_{14} \\
\sin \theta & \cos \theta & 0 & x_{24} \\
0 & 0 & 1 & x_{34} \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(22)

In the horizontal plane (Figure 18),

$$\tan \theta_i = \frac{x_{34} - P \sin \theta}{x_{44} - P \cos \theta} = \frac{x_{34} + P x_{12}}{x_{44} - P x_{22}}$$

(23)
Figure 18. Inverse kinematics
\[ \theta_1 = \text{atan2}(x_{u} - P \cdot x_{22}, x_{u} + P \cdot x_{12}) \] (24)

\[ \theta_2 = \theta - \theta_1 \]

\[ = \text{atan2}(x_{u}, -x_{12}) - \theta_1 \] (25)

**Horizontal distance in the vertical plane (Figure 18):**

\[ L \cos \theta_2 + M \cos(\theta_2 + \theta_3) \]

\[ = [(x_{u} + P \cdot x_{22})^2 + (x_{u} - P \cdot x_{22})^2]^{1/2} \] (26)

**Vertical distance:**

\[ Bz - L \sin \theta_2 - M \sin(\theta_2 + \theta_3) - N = x_{u} \] (27)

By re-arranging equations (26) and (27):

\[ \cos(\theta_2 + \theta_3) = [((x_{u} + P \cdot x_{22})^2 + (x_{u} - P \cdot x_{22})^2]^{1/2} - L \cos \theta_2)/M \] (28)

\[ \sin(\theta_2 + \theta_3) = (Bz - L \sin \theta_2 - N - x_{u})/M \] (29)

(28)\(^2\) + (29)\(^2\):

\[ 1 = \frac{[(x_{u} + P \cdot x_{22})^2 + (x_{u} - P \cdot x_{22})^2]^{1/2} - L \cos \theta_2}{M} \]

\[ + \frac{(Bz - L \sin \theta_2 - N - x_{u})}{M} \] (30)

Expand the right side of equation (30) and let

\[ A = 2 \frac{L}{M^2} (Bz - N - x_{u}) \] (31)

\[ B = -2 \frac{L}{M^2} [(x_{u} + P \cdot x_{22})^2 + (x_{u} - P \cdot x_{22})^2]^{1/2} \] (32)

\[ F = 1 - [(L/M)^2 - [(x_{u} + P \cdot x_{22})^2 + (x_{u} - P \cdot x_{22})^2]/M^2 - (Bz - N - x_{u})^2/M^2 \] (33)

We have

\[ B \cos \theta_2 - A \sin \theta_2 = F \] (34)

Therefore,

\[ \theta_2 = \text{atan2}(A, B) - \text{atan2}[(A^2 + B^2 - F^2)^{1/2}, F] \] (35)

By substituting \( \theta_2 \) into (28) and (29) and let...
C = \((\{(x_{34} + P + x_{12})^2 + (x_{34} - P + x_{12})^2\})^{1/2} - L \cos \theta_2\)/M \quad (36)

D = (Bz - L \sin \theta_2 - N - x_{34})/M \quad (37)

Finally,
\[ \theta_3 = \text{atan2}(C, D) - \theta_2 \quad (38) \]

The inverse kinematics program was executed. The result was used to program the robot for the unloading and loading operations.

5.4 Jacobian analysis of the MTS A-200 robot

Coordinates of end effector reference frame origin in the universal reference frame:

\[ x = \cos \theta_1[L \cos \theta_2 + M \cos(\theta_2 + \theta_3)] \quad (39) \]
\[ y = \sin \theta_1[L \cos \theta_2 + M \cos(\theta_2 + \theta_3)] \quad (40) \]
\[ z = Bz - N - L \sin \theta_2 - M \sin(\theta_2 + \theta_3) \quad (41) \]

Differentiation of the above equation gives the velocities of the end effector:

\[ \frac{dx}{dt} = - \sin \theta_1[L \cos \theta_2 + M \cos(\theta_2 + \theta_3)] \omega_1
- \cos \theta_1[L \sin \theta_2 + M \sin(\theta_2 + \theta_3)] \omega_2
- M \cos \theta_1 \sin(\theta_2 + \theta_3) \omega_3 \quad (42) \]
\[ \frac{dy}{dt} = \cos \theta_1[L \cos \theta_2 + M \cos(\theta_2 + \theta_3)] \omega_1
- \sin \theta_1[L \sin \theta_2 + M \sin(\theta_2 + \theta_3)] \omega_2
- M \sin \theta_1 \sin(\theta_2 + \theta_3) \omega_3 \quad (43) \]
\[ \frac{dz}{dt} = - [L \cos \theta_2 + M \cos(\theta_2 + \theta_3)] \omega_2
- M \cos(\theta_2 + \theta_3) \omega_3 \quad (44) \]
Where,

\[ w_1 = \frac{d\theta_1}{dt}, \]
\[ w_2 = \frac{d\theta_2}{dt}, \]
\[ w_3 = \frac{d\theta_3}{dt}. \]

Let \( \omega_x, \omega_y, \omega_z \) be the rotational velocities of the end effector in the universal reference frame,

\[ \omega_x = -2 \sin\theta_1 (\omega_2 + \omega_3) \]
\[ \omega_y = -2 \cos\theta_1 (\omega_2 + \omega_3) \]
\[ \omega_z = \omega_1 + \omega_4 \]

Differentiation of the velocities gives the accelerations of the end effector in the universal reference frame,

\[
\frac{d^2x}{dt^2} = \frac{d}{dt} \left( \frac{dx}{dt} \right) = -\cos\theta_1 (L \cos\theta_2 + M \cos(\theta_2 + \theta_3)) \omega_1^2
\]
\[ + \sin\theta_1 (L \sin\theta_2 \omega_2 + M \sin(\theta_2 + \theta_3) (\omega_2 + \omega_3)) \omega_1 \]
\[ - \sin\theta_1 (L \cos\theta_2 + M \cos(\theta_2 + \theta_3)) \omega_2 \]
\[ + \sin\theta_1 (L \sin\theta_2 + M \sin(\theta_2 + \theta_3)) \omega_2 \omega_3 \]
\[ - \cos\theta_1 (L \cos\theta_2 \omega_2 + M \cos(\theta_2 + \theta_3) (\omega_2 + \omega_3)) \omega_2 \]
\[ - \cos\theta_1 (L \sin\theta_2 + M \sin(\theta_2 + \theta_3)) \omega_3 \]
\[ + M \sin\theta_1 \sin(\theta_2 + \theta_3) \omega_1 \omega_3 \]
\[ - M \cos\theta_1 \cos(\theta_2 + \theta_3) (\omega_2 + \omega_3) \omega_3 \]
\[ - M \cos\theta_1 \sin(\theta_2 + \theta_3) \omega_3 \]

\[
\frac{d^2y}{dt^2} = \frac{d}{dt} \left( \frac{dy}{dt} \right) = \frac{d}{dt} \left( \frac{dy}{dt} \right)
\]
\begin{align*}
= & \sin\theta_1[L \cos\theta_2 + M \cos(\theta_2 + \theta_3)]w_1^2 \\
& - \cos\theta_1[L \sin\theta_2 \omega_2 + M \sin(\theta_2 + \theta_3)(\omega_2 + \omega_3)]w_1 \\
& + \cos\theta_1[L \cos\theta_2 + M \cos(\theta_2 + \theta_3)]\varepsilon_1 \\
& - \cos\theta_1[L \sin\theta_2 + M \sin(\theta_2 + \theta_3)]\omega_1\omega_2 \\
& - \sin\theta_1[L \cos\theta_2 \omega_2 + M \cos(\theta_2 + \theta_3)(\omega_2 + \omega_3)]w_2 \\
& - \sin\theta_1[L \sin\theta_2 + M \sin(\theta_2 + \theta_3)]\omega_2w_2 \\
& - M \cos\theta_1 \sin(\theta_2 + \theta_3) \omega_1 \omega_2 \\
& - M \sin\theta_1 \cos(\theta_2 + \theta_3)(\omega_2 + \omega_3)w_2 \\
& - M \sin\theta_1 \sin(\theta_2 + \theta_3) \varepsilon_3 \\
& + M \cos(\theta_2 + \theta_3) \varepsilon_3 \tag{49}
\end{align*}

\[ \frac{d^2z}{dt^2} = \frac{d}{dt} \left( \frac{dz}{dt} \right) \]

\[ = [L \sin\theta_2 \omega_2 + M \sin(\theta_2 + \theta_3)(\omega_2 + \omega_3)]w_2 \\
- [L \cos\theta_2 + M \cos(\theta_2 + \theta_3)]\varepsilon_2 \\
+ M \sin(\theta_2 + \theta_3)(\omega_2 + \omega_3)w_3 \\
- M \cos(\theta_2 + \theta_3) \varepsilon_3 \tag{50} \]

Where
\[ \varepsilon_1 = \frac{d(\omega_1)}{dt} = \frac{d^2(\theta_1)}{dt^2}, \]
\[ \varepsilon_2 = \frac{d(\omega_2)}{dt} = \frac{d^2(\theta_2)}{dt^2}, \]
\[ \varepsilon_3 = \frac{d(\omega_3)}{dt} = \frac{d^2(\theta_3)}{dt^2}. \]

Let \( \varepsilon_x, \varepsilon_y, \) and \( \varepsilon_z \) be the rotational accelerations of the end effector in the universal reference frame, then

\[ \varepsilon_x = -2 \cos\theta_1(\omega_2 + \omega_3)w_1 \\
- 2 \sin\theta_1(\varepsilon_2 + \varepsilon_3) \tag{51} \]
\[ \varepsilon_y = -2 \sin \theta_1 (w_2 + w_3) w_1 \]
\[ + 2 \cos \theta_1 (\varepsilon_2 + \varepsilon_3) \]
\[ \varepsilon_z = \varepsilon_1 + \varepsilon_4 \]

5.5 Servo control

Servo control was accomplished by four PID (Proportional, Integral and Derivative) loop control boards in the Daytronic mainframe. A block diagram of the PID control scheme (source: Daytronic product manual) is shown in Figure 19. From the block diagram it is obvious that the control scheme is not the same as the classical PID control, nevertheless the boards performed the function satisfactorily.

Each joint of the robot was controlled by one of the four PID loop control boards. They functioned independently. Because of the unique characteristics of the dynamics of each joint the P, I and D values for each board are significantly different. Since the dynamics of each joint are not readily available the P, I and D values can not be derived systematically. By following the instructions all values are derived on the base of trial and error such that a critically damped system can be achieved for each of the joints. The P, I and D values for all four loop control boards are listed in Table 6.
Table 6. Servo control P, I, and D factors

<table>
<thead>
<tr>
<th>joint</th>
<th>P</th>
<th>I</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>47</td>
<td>115</td>
</tr>
<tr>
<td>3</td>
<td>28</td>
<td>80</td>
<td>105</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>105</td>
<td>85</td>
</tr>
</tbody>
</table>

Figure 19. PID servo control scheme
Joint position feedback were performed by RVDTs. Those are standard analog sensing devices. The RVDT signals were conditioned by two LVDTs conditioning boards inside the Daytronic mainframe. RVDTs and LVDTs work on the same principle. As a result, ± 5 V analog position signals and digital position data are available from the conditioning boards. Since the PID loop control boards accept either digital or analog response signals, analog format was chosen to speed up the servo loops. All four servo control loops are in real time analog format to achieve the best performance.

Set points were provided by the supervisory computer in digital format.

5.6 Supervisory Control

The analog servo control drove the robot to the desired positions. It is up to the supervisory computer to constantly update the position command so that the robot could reach all the specified positions to perform the desired operation. The control scheme in this fashion is frequently called point to point control in contrast to continuous path control. Only a limited number of pre-specified points are important for point to point control robots. The control program directs the robot to go through those points sequentially. However, the trajectory of the robot end effector between two adjacent points was not directly controlled by the program. Therefore the actual trajectory between two adjacent points can take any
form and was not predictable. For the case of the container handling operation accurate end effector trajectory was not necessary. Only specified discrete positions are important for the successful operation. However, there is no limit on the number of points that can be programmed for the supervisory computer used in this project. Therefore, accurate end effector trajectories could be achieved with a large number of programmed points since point to point control with very small interval approximated the so called continuous path control. Obstacle avoidance can be achieved by programming extra points around the obstacles.

The computer program in PASCAL was developed on the HP computer for the supervisory control. Besides the coordination module, kinematics and Jacobian modules were also developed. The program is listed in Appendix A for reference.
CHAPTER VI
EXTENDABLE AND RETRACTABLE BELT CONVEYOR

6.1 Introduction

The proposed conveyor consists of 10 - 12 sections with each one having a slightly larger cross section than that of the preceding one. Each section has a length of about 3 meters and can slide into the following section, as shown in Figure 20. The cross section of the conveyor is a "rectangular C". When the conveyor retracts the extra belt is stored loose in the box in the fashion of a printer ribbon. The belt tension and drive is provided by the two pairs of rollers outside the box. A three section prototype of the belt conveyor was constructed to test and evaluate the concept.

Since the conveyor is extendable and retractable it is important to keep it moving straight during the process. Currently there is no mechanism on the conveyor to ensure a straight motion. An extra wheel on the conveyor that rolls along a drain ditch on the greenhouse floor could serve the purpose of guiding the system.

There are different ways to implement the conveyor. One of them is proposed in the following section. Lab tests of the three section prototype proved that the concept worked.
Figure 20. Extendable and retractable belt conveyor

MATERIALS

3.18 MM ALUMINUM SHEET
3 PIECES
3.05 M LONG EACH
6.2 A feasible concept

A functional sketch of the belt conveyor is shown in Figure 20. As mentioned earlier the conveyor is composed of multiple sections. The conveyor belt is driven by a variable speed, bi-directional electric motor through a chain mechanism and two pairs of rollers. The conveyor can be extended by pulling a steel cable with a motorized roller (driven by preferably another variable speed motor).

Figure 21 shows the mechanism that drives the conveyor belt in both directions. The two pairs of rollers are fixed on both ends of the belt storage box, are spring loaded and can be adjusted to provide variable driving force. The chain gear drives for both the two pairs of rollers are only one directional. That means they can provide drive torque in only one direction. The driving power comes from the variable speed, bi-directional electric motor. When the belt moves from left to right the pair of rollers on the right side provides the driving force. The spring on the left side rollers is released and allows the belt to slide out at its own pace. On the other hand, the left side rollers drive the belt from right to left with spring load released for the right side rollers.

For the container unloading operation, the conveyor belt should halt momentarily after the container collector holds eight containers in position. After the robot arm lifts the containers up the conveyor belt resumes its motion. The control circuit for the electric motor is shown in Figure 22.
Figure 21. Conveyor belt drive mechanism

Figure 22. Control circuit for conveyor AC motor
The control circuit is composed of a solid state relay and eight spring loaded switches that detect the presence of eight containers. The DataPac provides 5 V DC voltage to the control circuit through its logic output. If not all eight containers are in position to turn off the switches, the control circuit is a closed loop. Therefore the DC voltage will apply to the solid state relay and in turn it connects the AC motor to the power supply. The motor drives the conveyor belt to advance the containers. The robot arm may stop momentarily for a signal from the DataPac. When all eight containers are in position to turn off the switches, the control circuit is opened. There will be no voltage across the relay and the motor stops. The control circuit also sends a logic signal to the DataPac so that the robot arm proceeds to unload the containers. After the containers are lifted up, the control circuit closes again and allows the motor to drive the conveyor belt so that another set of containers can be positioned.

Figure 23 displays the conveyor extension mechanism. The motorized roller pulls the steel cable through a pulley to extend the second section of the conveyor. The extension of the second section in turn pulls out the third section. All sections will extend the same length. As the result the conveyor extends twice that length for the three section prototype. The conveyor keeps the length if it is locked, otherwise the conveyor belt provides the force for the
CONVEYOR EXTENSION MECHANISM

CONVEYOR SECTION

PULLEY

STEEL CABLE

MOTORIZED ROLLER

Figure 23. Conveyor extension mechanism
conveyor to retract as the motor rotates in reverse direction to release the cable.

This extension mechanism worked for the three section prototype. However it may not work for the full size conveyor with ten sections due to the tremendous increase in friction. An alternative is to directly drive the two wheels that support the robot at the free end of the conveyor. Below is an estimation of the friction and the drive force with the assumption that the conveyor belt remains stationary to the largest section of the conveyor.

The maximum friction occurs when all sections are almost fully extended. So the maximum friction between belt and aluminum sections can be found as,

\[ f_w = 9 \times (3.05/0.2 \times 22.23 + 1506 \times 9.8 \times 3.05 \times 0.0032 \times 0.2) \times 0.50 \]

\[ = 1656.30 \text{ N} \]

where 1506 kg/m² is the density of the rubber belt, 0.0032 m is the thickness, 0.2m is the width of the belt, and 0.50 is the sliding friction coefficient of rubber on aluminum surface (all friction coefficients used in this section are from Marks' Standard Handbook for Mechanical Engineers by Baumeister et al., 1987).

Aluminum sections are not in direct contact with each other. Teflon strips are bonded to the outside of smaller sections at the end so that the larger section slides on the teflon strips. The friction coefficient of aluminum on teflon
is 0.04. Hence

\[ f_r = 9 \times (3.05/0.2 \times 22.23 + 1506 \times 9.8 \times 0.0032 \times 0.2 \times 3.05)/2 \times 0.04 \]

\[ = 66.25 \text{ N} \]

If all other friction forces are to be neglected the total friction force is

\[ f = f_r + f_n \]

\[ = 1722.55 \text{ N} \]

The sliding friction coefficient of a properly inflated rubber tire on dry, firm soil surface can be estimated at 0.6. Therefore to get a drive force of 1722.55 N, the vertical weight on the two wheels should at least be

\[ W = f/0.6 \]

\[ = 2870.92 \text{ N} \]

This weight is reasonable if the weight of the belt storage box is added to the relatively heavy robot base. A heavy robot base is necessary to balance the dynamic bending moment due to joint accelerations. The maximum bending moment found in Chapter IV was 386.25 Nm. The weight found above is one practical way to counter-balance the bending moment so that the robot will not tilt over. Hence the minimum distance between the two wheels is

\[ L = 2 \times 386.25 \text{ Nm}/2870.92 \text{ N} \]

\[ = 0.27 \text{ m} \]
6.3 Conveyor design

For the purpose of stress analysis, each section of the conveyor was simplified as a simply supported beam, as shown in Figure 24. Each section is 3.05 m long and the smallest section is 0.25 m wide and has a cross section shown in Figure 25.

**Figure 24. Stress analysis of the smallest conveyor section**
The conveyor is made from surface hardened aluminum sheet with 3.18 mm thickness. Let's assume that a 90.72 kg person accidentally steps on the center of the smallest section of a fully extended conveyor. The force and bending moment acting on the conveyor were calculated below.

A ---- area of conveyor cross section
d ---- location of center of gravity from top surface

$I_\alpha$ --- area moment of inertia about principle axis

$[\sigma]$ -- material tensile stress

$\sigma_{\text{max}}$ --- maximum stress on the conveyor cross section

$E$ ---- Young's module

$\rho$ ---- mass density

$L$ ---- length of conveyor section

$y$ ---- deflection in the middle of the conveyor section

$M_i$ ---- bending moment due to 90.72 kg person

$M_t$ ---- bending moment due to containers and conveyor weight

$M_{\text{max}}$ -- maximum bending moment on the conveyor cross section

$W_i$ ---- total weight of one conveyor section

$W_t$ ---- total weight of all containers on top of one conveyor section

$P$ ---- weight of the person

Cross sectional area (composite area of one top rectangular, two side rectangular and two bottom rectangular):

$$A = 247.65 \times 3.18 + 2 \times (38.10 - 2 \times 3.18) \times 3.18$$
$$+ 2 \times 3.18 \times 25.40$$
$$= 1150.94 \text{ mm}^2$$

Location of the neutral axis from top surface:

$$d = \{(247.65 \times 3.18) \times 1.59 + 2 \times (38.10 - 2 \times 3.18)$$
$$\times 3.18 \times 38.10/2 + 2 \times 3.18 \times 25.40 \times (38.10$$
Area moment inertia (Parallel-Axis Theorem, Hibbeler, 1983):

\[
I_m = \frac{1}{12} x 247.64 x (3.18)^3 + 247.65 x 3.18 x (9.55 - 1.59)^2 + 2 \times \frac{1}{12} x 3.18 \times (38.10 - 2 x 3.18)^3 + 2 x (38.10 - 2 x 3.18) x 3.18 x (38.10/2 - 9.55)^2 + 2 x 25.40 x (3.18)^3 + 2 x 25.40 x 3.18 x (38.10 - 1.59 - 9.55)^2
\]

\[= 2.03 \times 10^7 \text{ mm}^4\]

For the property of aluminum:

\[\sigma = 186.17 \text{ MPa}\]
\[E = 68,950 \text{ MPa}\]
\[\rho = 2643 \text{ kg/m}^3\]

Therefore the weight of the section is:

\[W_i = A \times L \times \rho g = 90.92 \text{ N}\]

The 3.785 liter size containers take 0.20 m space each on the conveyor and weigh 22.25 N each, consequently the total weight of containers on top of one section of the conveyor is:

\[W_c = 22.25 \times 3.05/0.2\]

\[= 339.31 \text{ N}\]

Bending moment due to P:

\[M_i = P \times L/4\]

\[= 889.06 \times 3.05/4\]

\[= 677.91 \text{ Nm}\]

Bending moment due to conveyor and container weight:
\[ M_2 = (W_1 + W_2) \times L/8 \]
\[ = (90.92 + 339.31) \times 3.05/8 \]
\[ = 164.03 \text{ Nm} \]

**Maximum bending moment:**

\[ M_{\text{max}} = M_1 + M_2 \]
\[ = 841.94 \text{ Nm} \]

**Maximum stress:**

\[ \sigma_{\text{max}} = \frac{M_{\text{max}}}{I_x} \times y_{\text{max}} \]
\[ = 841.94 / (2.03 \times 10^7) \times (38.10 - 9.55) \times 10^3 \]
\[ = 118.41 \times 10^6 \text{ N/m}^2 \]
\[ = 118.41 \text{ MPa} \]

**Safety factor:**

\[ n = \frac{[\sigma]}{\sigma_{\text{max}}} \]
\[ = \frac{186.17}{118.41} \]
\[ = 1.57 \]

**Maximum deflection in the middle due to the 889.06 N transverse load:**

\[ f_1 = \frac{PL^/}{(48 \times EI)} \]
\[ = \frac{(889.06 \times 3.05^/)}{(48 \times 68950 \times 10^6} \]
\[ \times 2.03 \times 10^7) \]
\[ = 3.755 \times 10^2 \text{ m} \]
\[ = 37.55 \text{ mm} \]

**Maximum deflection in the middle due to uniformly-distributed transverse load (container and conveyor weight):**

(Mark's Mechanical Engineering Handbook)

\[ f_2 = 5 (W_1 + W_2) \times L^/ / (384 \times EI) \]
\[ f_2 = 5 \left(90.92 + 339.31 \right) \times 3.05^3 / \left(384 \times 68950 \times 10^6 \right) \times 2.03 \times 10^3 \]
\[ = 1.136 \times 10^7 \text{ m} \]
\[ = 11.36 \text{ mm} \]

The total static deflection in the middle of the section is:

\[ f_{\text{mm}} = f_i + f_2 = 48.91 \text{ mm} \]

The 48.91 mm deflection in the middle will not destroy the conveyor. However it will certainly affect the operation. It is not advised to put heavy objects on the conveyor during operation.

A three section prototype of the conveyor was constructed for the lab test. The stress analysis on the largest section was also conducted following the same procedure above. The maximum bending stress occurred on the bottom surface of the section and was found to be 40.78 MPa. This number is very small comparing to the allowed tensile stress of 187.17 MPa. Therefore holes can be punched on the top surfaces of larger sections to reduce structure weight and also to allow soil to fall off the conveyor.
CHAPTER VII
RESULTS AND DISCUSSION

Robot position data from the CATIA simulation was used to program the MTS A-200 robot for the unloading/loading operations. The principle of programming the robot in such fashion is known as off-line programming since the robot arm is not involved in the programming stage. The position data were validated by the inverse kinematics program. Sample data of the inverse kinematics program execution are listed in Appendix B.

The MOVE_TO procedure of the supervisory control program was modified such that the computer could receive the robot joint positions, velocities, and accelerations from the DataPac and store them on a disk. The modified MOVE_TO procedure is listed in APPENDIX C for reference. Information of one complete cycle of loading operation was recorded and listed in Appendix D for reference. One set of typical data were plotted in Figures 26 through 29 for each of the four joints. Compared with the ideal operation profile suggested in Figure 5, it can be noted that the real case is far different from the ideal assumption. The difference will contribute significantly to the simulated robot cycle time as discussed later in this chapter.
Figure 26. Waist joint position, velocity, and acceleration
Operation Profile

Shoulder

- Position, deg
- Velocity, deg/sec
- Acceleration, deg/sqr sec

Figure 27. Shoulder joint position, velocity, and acceleration
Figure 28. Elbow joint position, velocity, and acceleration
Operation Profile
Wrist Roll

- Position, deg
- Velocity, deg/sec
- Acceleration, deg/sq sec

Figure 29. Wrist roll joint position, velocity, and acceleration
The Jacobian program was executed on the recorded data of joint positions, velocities, and accelerations. Program execution resulted in velocities and accelerations of the end effector in the universal reference frame and these data are listed in Appendix E for reference.

The real cycle time of the MTS A-200 robot for the unloading operation in our test is 19.2 seconds. This is only for one set of containers. The robot arm didn't move at the maximum velocity and acceleration for the lab test. This occurred because the containers slid off the end effector if maximum acceleration was applied in the direction opposite the \( X_e \) direction (refer to Figure 17). The robot actually moved at the slower speed as listed under Actual velocity in Table 1. The upstroke time was around 0.5 second. The computer simulation results show 11.4 seconds for the same velocity and acceleration. There are two major reasons for the difference in robot cycle time between the lab tests and the computer simulations. One is that the robot arm stopped between each operation step. The second is that the real joint velocity profile differs from the ideal velocity profile used for the computer simulation. For the real case, the robot joints didn't keep the speed after acceleration, rather they decelerated immediately after the acceleration (Figure 26 to Figure 29), and hence have lower average velocities.

The computer simulation study showed that the robot can successfully pick up containers from the conveyor and place
them on the greenhouse floor in a predefined pattern. It also proved to be useful to gain insight on robot operation.

Lab tests on the three section prototype of the extendable belt conveyor demonstrated that the concept worked. The conveyor can move the containers in both direction with minimum manual assistance. The container collector worked especially well. It can successfully hold three containers in place and stop the conveyor belt momentarily until after the robot arm picked up the containers. The conveyor also worked well for the loading operation.

However for a full size conveyor with 10 or more sections it is very doubtful if the same design can be used. This is because the conveyor extension mechanism will have to overcome a much larger friction force to extend the conveyor and also the belt storage box will have to handle much more belt when the conveyor retracts. Different concepts are being formulated in the lab and will eventually be evaluated against the current mechanisms.
8.1 Conclusions

The following conclusions can be drawn from the study:

1. Computer graphics simulation proved useful in robot system development.

2. Computer simulation made off-line programming of the robot possible. For the point to point control nursery robot, graphical simulation displayed the actual trajectory the robot arm took even though it was not programmed, and therefore can assist in programming the robot to avoid obstacles.

3. A three section prototype of the extendable and retractable belt conveyor was constructed and tested, and the concept was found to be feasible.

4. The robot controller worked reasonably well. It provided enough repeatability for continuous operation. The current control algorithm, however, allows the robot to stop between steps, and to decelerate immediately after acceleration, and therefore gives a longer cycle time.

5. The fork shaped end effector can be used to unload or load containers. However it limited the maximum acceleration. Currently the maximum acceleration allowed opposite the $X_e$.
direction (refer to Figure 17) is less than $3.92 \text{ m/s}^2 (0.4g)$.

6. The cross-sections of the square aluminum tube used for the vertical and horizontal links of the proposed nursery robot were selected to be $10.16 \text{ cm} \times 10.16 \text{ cm}$ and $6.76 \text{ cm} \times 6.76 \text{ cm}$ respectively.

7. From the dynamic analysis it was demonstrated that the robot arm would be quite flexible. Therefore it can be treated as a flexible manipulator. Hence the control algorithm can be modified to achieve the best performance.

8.2 Recommendations for Future Study

1. More work should be done on the conveyor so that the computer can control the extension and retraction, sense its position, and change the direction of the belt movement.

2. The robot controller should be modified to include velocity feedback to control both joint position and velocity so that the cycle time can be reduced.

3. The nursery robot arm should be constructed so that system integration can be done and the complete robot system can be tested.

4. Economic analysis should be conducted to study the feasibility of using the nursery robot for commercial greenhouse production.

5. An automatic handchanger should be developed if the robot handles different sizes of containers frequently.
6. The extendable and retractable belt conveyor can be a stand alone unit. It can be used to transport containers in small scale greenhouses where robotic systems would not be possible.
REFERENCES


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36). Waldron, K. J., Mechanical Design of Manipulators and Robots: Class Notes for ME752, The Ohio State University, Columbus, Ohio, 1984.


APPENDIX A

COMPUTER PROGRAM FOR SUPERVISORY CONTROL

$UCSD,SYSPROG,SWITCH_STRPOS$
$REF 'B9826:',REF 70$

PROGRAM ROBOT(output,keyboard);

import
 iocomasm,  
iodeclarations,  
general_1,  
general_2,  
general_3,  
general_4,  
hpib_0,  
hpib_1,  
hpib_2,  
hpib_3,  
sysdevs;

$SEARCH•RAM:GRAPHICS.'$

import
 dgl_lib,  
dgl_inq;

type
 array4 = array[1..4] of real;  
matx44 = array[1..4,1..4] of real;

var
 d: array4;  
e: array4;  
f: integer;  
comm: string[80];  
stime: string[80];  
angle: array4;  
time: integer;  
I,J,K: integer;  
dtime: real;  
X: matx44;  
c: array4;  
pos: array4;
home: array4;
angle1: array4;
angle2: array4;
angle3: array4;
angle4: array4;
angle5: array4;
angle6: array4;
angle7: array4;
angle8: array4;
left1: array4;
left2: array4;
left3: array4;
left4: array4;
left5: array4;
left6: array4;
left7: array4;
left8: array4;
left9: array4;
left10: array4;
left11: array4;
left12: array4;
left13: array4;
left14: array4;
left15: array4;
left16: array4;
left17: array4;
left18: array4;
left19: array4;
left20: array4;
right1: array4;
right2: array4;
right3: array4;
right4: array4;
right5: array4;
right6: array4;
right7: array4;
right8: array4;
right9: array4;
right10: array4;
right11: array4;
right12: array4;
right13: array4;
right14: array4;
right15: array4;
right16: array4;
right17: array4;
right18: array4;
right19: array4;
right20: array4;
sign: array4;
PRINTOUT: TEXT;
error: integer;
CONST
PI = 3.1416;
L = 1.27;
M = 1.27;
N = 1.02;
BZ = 0.61;
P = 0.17;

$INCLUDE' ROBOT:SET_UP.TEX'T$
$INCLUDE' ROBOT:DIRKIN.TEX'T$
$INCLUDE' ROBOT:INVKIN.TEX'T$
$INCLUDE' ROBOT:JACOBN.TEX'T$
$INCLUDE' ROBOT:INVJCB.TEX'T$
$INCLUDE' ROBOT:UNLOAD.TEX'T$
$INCLUDE' ROBOT:LOAD.TEX'T$

procedure main_menu;
var
choice: char;
cont: boolean;

begin
cont:= true;
while cont do
begin
  clear_display;
gotoxy(0,1);
  writeln('Main Menu: ');
  writeln('  0. Quit');
  writeln('  1. Set up Daytronic');
  writeln('  2. Direct kinematics');
  writeln('  3. Inverse kinematics');
  writeln('  4. Jacobian');
  writeln('  5. Inverse Jacobian');
  writeln('  6. Unload containers');
  writeln('  7. Load containers');
  writeln('  sequence: turn on amplifier');
  writeln('  turn on DataPac');
  writeln('  turn on hydraulic power supply');
  writeln('  wait till the robot stabilized');
  writeln('  press 6');
  writeln('  sequence: turn on amplifier');
  writeln('  turn on DataPac');
  writeln('  turn on hydraulic power supply');
  writeln('  wait till the robot stabilized');
writeln('turn the EEPROM switch on');
writeln('press 7');
gotoxy(0,22); write('Enter choice(0 - 7) --> '); repeat
  read(keyboard, choice);
until choice in ['0','1','2','3','4','5','6','7'];
case choice of
  '0': cont:= false;
  '1': SET_UP;
  '2': DIRKIN;
  '3': INVERKIN;
  '4': JACOBN;
  '5': INVJCB;
  '6': UNLOAD;
  '7': LOAD;
otherwise cont:= true;
end;
end;
end;

begin
  graphics_init;
display_init(3,0,error);
ioinitialize;
main_menu;
iouninitialize;
graphics_term
end.

procedure set_up;

VAR
  ISC: TYPE_ISC;
  A: STRING[255];
  B: REAL;
  C: CHAR;

BEGIN
  SET_TIMEOUT(7,1.0);
  C:='N';
  REPEAT
    WRITESTRINGLN(1,'ENTER COMMAND:');
    READSTRING_UNTIL(CHR(13),2,A);
    WRITESTRINGLN(702,A);
    TRY
      READNUMBERLN (702,B);
      WRITENUMBERLN(1,B);
    RECOVER BEGIN
      IF ESCAPECODE=IOESCAPECODE
THEN BEGIN
  IF (IOE_RESULT = IOE_TIMEOUT)
      AND (IOE_ISC = 7)
      THEN BEGIN
        IORESET(7);
      END
      ELSE BEGIN
        ESCAPE(ESCAPECODE);
      END;
  END
  ELSE BEGIN
    ESCAPE(ESCAPECODE);
  END;
END;

PROCEDURE DIRKIN;

{*********** FILE DIRKIN.TEXT ***********}
{*************************************************}
{  PROCEDURE DIRKIN }
{ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * }
{   *********************************************************}
{   }{  PROGRAMMER: Changhe Chen }{  }
{   }{  DATE: SEPT. 15, 1989 }{  }
{   }{  FUNCTION: To calculate the homogeneous transform for }{  }
{   }{   the MTS-200 industrial robot based on the }{  }
{   }{   joint angles furnished }{  }
{   }{  USER GUIDE: DIRKIN(ANGLE,X) }{  }
{   }{  INPUT: ANGLE --- Joint angles in degree away from }{  }
{   }{   home position }{  }
{   }{  OUTPUT: X -- Homogeneous transform matrix of the }{  }
{   }{   end effector in reference coordinates }{  }
{   }{ *************************************************}

TYPE
  ARRAY5 = ARRAY[1..5] OF REAL;
  MATX44 = ARRAY[1..4,1..4] OF REAL;

VAR
  X: MATX44;
  ANGLE: ARRAY5;
  B1,B2,B3,B4,B5: REAL;
CONST
  PI = 3.14159;
  L = 1.27;
  M = 1.27;
  N = 1.02;
  BZ = 0.61;

BEGIN (*DIRKIN*)
  B1 := ANGLE[1]*PI/180.0;
  B2 := (ANGLE[2]-90.0)*PI/180.0;
  B3 := (ANGLE[3]+90.0)*PI/190.0;
  B4 := B3-B2;
  B5 := ANGLE[5]*PI/180.0;
  X[1,1] := COS(B1)*COS(B2+B3+B4)*COS(B5) -
             SIN(B1)*SIN(B5);
  X[2,1] := SIN(B1)*COS(B2+B3+B4)*COS(B5) +
             COS(B1)*SIN(B5);
  X[3,1] := -SIN(B2+B3+B4)*COS(B5);
  X[4,1] := 0.0;
  X[1,2] := -COS(B1)*COS(B2+B3+B4)*SIN(B5) -
             SIN(B1)*COS(B5);
  X[2,2] := -SIN(B1)*COS(B2+B3+B4)*SIN(B5) +
             COS(B1)*COS(B5);
  X[3,2] := SIN(B2+B3+B4)*SIN(B5);
  X[4,2] := 0.0;
  X[1,3] := COS(B1)*SIN(B2+B3+B4);
  X[2,3] := SIN(B1)*SIN(B2+B3+B4);
  X[3,3] := COS(B2+B3+B4);
  X[4,3] := 0.0;
  X[1,4] := -N*X[1,3] + COS(B1)*(M*COS(B2+B3) + L*COS(B2));
  X[4,4] := 1.0
END; (*DIRKIN*)

FUNCTION ATAN2(E,F: REAL): REAL;
BEGIN
  IF E > 0.0 THEN ATAN2 := ARCTAN(F/E);
  IF E < 0.0 THEN IF F >= 0.0 THEN
    ATAN2 := PI - ARCTAN(F/ABS(E))
  ELSE ATAN2 := -PI + ARCTAN(ABS(F)/ABS(E));
  IF E = 0.0 THEN IF F > 0.0 THEN ATAN2 := PI/2.0
  ELSE ATAN2 := -PI/2.0
END; (ATAN2)
PROCEDURE INVKIN(X: matx44);

{*********************** FILE INVKIN.TEXT ***********************}

{*******************************************************************************
 { PROCEDURE INVKIN }
 {*******************************************************************************

*************** PROGRAMMER: Changhe Chen 
 DATE: May 17, 1990 
 FUNCTION: To calculate the joint angles based on the 
 homogeneous transform furnished 
 USER GUIDE: INVKIN(X, ANGLE) 
 INPUT: X --- Homogeneous transform matrix of the 
 end effector in reference 
 coordinates 
 OUTPUT: ANGLE --- Joint angles in degree away 
 from the home position 
 STATUS_SET --- Status of inverse 
 Kinematics solution 
*******************************************************************************

TYPE

STATUSS = (VALID_SOLUTION, REACH_EXCEEEDED,
LIMITS_EXCEEEDED);

VAR

STAT: STATUSS;
S1, S2, S3, S4: REAL;
A, B, F, R, C: REAL;

BEGIN {*INVKIN*}

S1 := ATAN2((X[1,4] - P*X[2,2]), (X[2,4] + P*X[1,2]));
IF X[1,2] = 0.0 THEN
BEGIN
   IF X[2,2] < 0.0 THEN IF S1 > 0.0 THEN
      S4 := PI - S1
   ELSE S4 := -PI - S1
   ELSE S4 := -S1
END
END ELSE BEGIN

S4 := ATAN2(X[2,2], -X[1,2]) - S1

END;
A := 2.0*(BZ-N-X[3,4])/M;
B := -2.0/M*SQRT(SQR(X[2,4]
   + P*X[1,2]) + SQR(X[1,4] - P*X[2,2]));
F := -(SQR(X[2,4] + P*X[1,2]) + SQR(X[1,4]
   - P*X[2,2]))/SQR(M) - SQR((BZ-N-X[3,4])/M);
C := A*A + B*B - F*F;


IF C >= 0 THEN BEGIN
S2 := ATAN2(A,B) - ATAN2(SQRT(C),F);
A := (SQRT(SQR(X[2,4] + P*X[1,2])
     + SQR(X[1,4] - P*X[2,2])) - L*COS(S2))/M;
B := (-X[3,4]+BZ-N-L*SIN(S2))/M;
S3 := ATAN2(A,B) - S2;
ANGLE[1] := S1*180.0/PI;
ANGLE[2] := 105.0 + S2*180.0/PI;
ANGLE[3] := S3*180.0/PI - 90.0;
ANGLE[4] := S4*180.0/PI;
STAT := VALID_SOLUTION;
IF (ANGLE[1] > 120.0) OR (ANGLE[1] < -120.0) THEN STAT := LIMITS_EXCEEDED;
ELSE BEGIN
STAT := REACH_EXCEEDED END;
END;
IF STAT = REACH_EXCEEDED THEN Writeln(PRINTOUT, STAT)
ELSE Writeln(PRINTOUT, 'ROBOT: ANGLE. TEXT');
Writeln(PRINTOUT, ANGLE[1], ',', ANGLE[2],
',', ANGLE[3], ',', ANGLE[4], ',', STAT);
Writeln(PRINTOUT);
END; (*INVKIN*)

PROCEDURE INVERKIN;
VAR I,J,K: INTEGER;
BEGIN
REWRITE(PRINTOUT, 'ROBOT:ANGLE.TEXT');
FOR I:=1 TO 4 DO BEGIN
  FOR J:=1 TO 4 DO BEGIN
    X[I,J] := 0.0;
  END;
  X[3,3] := 1.0;
  X[4,4] := 1.0;
  X[1,1] := 1.0;
  X[2,2] := 1.0;
  X[1,4] := -0.69;
X[2,4] := 1.17;
X[3,4] := 0.61;
INVKIN(X);
X[3,4] := 1.00;
INVKIN(X);
X[1,4] := -0.46;
INVKIN(X);
X[3,4] := 0.61;
INVKIN(X);
X[1,4] := -0.23;
INVKIN(X);
X[3,4] := 1.00;
INVKIN(X);
X[1,4] := 0.0;
INVKIN(X);
X[3,4] := 0.61;
INVKIN(X);
X[1,4] := 0.23;
INVKIN(X);
X[3,4] := 1.00;
INVKIN(X);
X[1,4] := 0.46;
INVKIN(X);
X[3,4] := 0.61;
INVKIN(X);
X[1,4] := 0.69;
INVKIN(X);
X[3,4] := 1.00;
INVKIN(X);
X[1,4] := -1.00;
X[2,2] := -1.00;
X[1,4] := -0.69;
INVKIN(X);
X[3,4] := 1.00;
INVKIN(X);
X[1,4] := -0.46;
INVKIN(X);
X[3,4] := 0.61;
INVKIN(X);
X[1,4] := -0.23;
INVKIN(X);
X[3,4] := 1.00;
INVKIN(X);
X[1,4] := 0.00;
INVKIN(X);
X[3,4] := 0.61;
INVKIN(X);
X[1,4] := 0.23;
INVKIN(X);
X[3,4] := 1.00;
INVKIN(X);
X[1,4] := 0.46;
INVKIN(X);
X[3,4] := 0.61;
INVKIN(X);
X[1,4] := 0.69;
INVKIN(X);
X[3,4] := 1.00;
INVKIN(X);
X[1,1] := 0.0;
X[2,2] := 0.0;
X[2,1] := -1.0;
X[1,2] := 1.0;
X[1,4] := 1.37;
X[2,4] := 0.38;
X[3,4] := 0.61;
INVKIN(X);
X[2,4] := 0.0;
INVKIN(X);
X[3,4] := 0.94;
INVKIN(X);
X[2,4] := 0.38;
INVKIN(X);
X[2,1] := 1.0;
X[1,2] := -1.0;
INVKIN(X);
X[3,4] := 0.61;
INVKIN(X);
X[2,4] := -0.38;
INVKIN(X);
CLOSE(PRINTOUT, 'SAVE')

END;

PROCEDURE JACOBN;

{*******************************************************

} { 
{ PROGRAMER: Changhe Chen 
{ DATE: May 14, 1990 
{ FUNCTION: To calculate the end effector velocity and 
{ acceleration from the furnished joint rates 
{ and joint accelerations 
{ USER GUIDE: jacobn(angle, ang_rate, end_speed) 
{ INPUT: ang_rate --- joint rates in angle/second 
{ angle --- joint angles in degree away from 
{ robot home position 
{ ang_acce --- joint accelerations in degree 
{ per second square 
{ OUTPUT: end_speed --- translational and rotational 
{ velocities of the end effector 
{ end_acce --- translational and rotational 
{ accelerations of the end effector 
{ } 
{*******************************************************}
type
array4 = array[1..4] of real;
array6 = array[1..6] of real;

var
angle: array4;
rate: array4;
acce: array4;
ang_rate: array4;
ang_acce: array4;
end_speed: array6;
end_acce: array6;
b1, b2, b3, b4, b5: real;
i, j: integer;
datain: file of real;
dataout: text;
dtime: real;
vel: real;
acc: real;

const
pi = 3.1416;
l = 1.27;
m = 1.27;
n = 1.02;
bz = 0.61;

begin
reset(datain, 'B9826:JOINT');
rewrite(dataout, 'B9826:XYZ. TEXT');
while not eof(datain) do
begin
for i := 1 to 4 do
begin
read(datain, dtime);
read(datain, angle[i]);
read(datain, rate[i]);
read(datain, acce[i]);
ang_rate[i] := rate[i]*pi/180.00;
ang_acce[i] := acce[i]*pi/180.00
end;
b1 := angle[1]*pi/180.00;
b2 := (angle[2] - 105.00)*pi/180.00;
b3 := (angle[3] + 90.00)*pi/180.00;
b4 := b3 + b2;
b5 := angle[4]*pi/180.00;
end_speed[1] := -sin(b1)*(l*cos(b2) + m*cos(b2+b3))
*ang_rate[1] - cos(b1)*(l*sin(b2)
+ m*sin(b2+b3))*ang_rate[2]
- m*cos(b1)*sin(b2+b3)*ang_rate[3];
end_speed[2] := cos(b1)*(1*cos(b2) + m*cos(b2+b3))
  *ang_rate[1] - sin(b1)*(1*sin(b2) + m*sin(b2+b3))*ang_rate[2] - m*sin(b1)*sin(b2+b3)*ang_rate[3];
end_speed[3] := - (l*cos(b2) + m*cos(b2+b3))
  *ang_rate[2] - m*cos(b2+b3)
  *ang_rate[3];
end_acc[1] := cos(b1)*(1*cos(b2) + m*cos(b2+b3))
  *sqr(ang_rate[1]) + sin(b1)*(1*sin(b2) + m*sin(b2+b3))
  *ang_rate[1] - sin(b1)*(1*cos(b2) + m*cos(b2+b3))
  *ang_rate[2] - cos(b1)*sin(b2+b3)*ang_rate[3];
end_acc[2] := - sin(b1)*(1*cos(b2) + m*cos(b2+b3))
  *sqr(ang_rate[1]) - cos(b1)*(1*sin(b2) + m*sin(b2+b3))
  *ang_rate[1] + cos(b1)*sin(b2+b3)*ang_rate[3];
end_acc[3] := (1*sin(b2)*ang_rate[2]+m*sin(b2+b3))
  - 1*cos(b2) + m*cos(b2+b3)*ang_acce[2]
  + m*sin(b2+b3)*(ang_rate[2] + ang_rate[3])*ang_rate[3]
  - m*cos(b2+b3)*ang_acce[3];
vel := sqrt(sqrt(end_speed[1]) + sqrt(end_speed[2]) + sqrt(end_speed[3]));
acc := sqrt(sqrt(end_acce[1]) + sqrt(end_acce[2]) + sqrt(end_acce[3]));
writeln(dataout, 'v ', end_speed[1], ', ', end_speed[2], ', ', end_speed[3], ', ', vel);
writeln(dataout, 'a ', end_acce[1], ', ', end_acce[2], ', ', end_acce[3], ', ', acc)
end;
close(dataout, 'SAVE ')
end; (* JACBN *)

PROCEDURE INVJCB;

(* ******************************************************)
(* PROGRAMMER: Changhe Chen  *)
(* DATE: November 9, 1989   *)
(* FUNCTION: To calculate joint rates from both the  *)
(* translational and rotational velocities  *)
(* of the end effector      *)
(* USER GUIDE: invjcb(angle, end_speed, ang_rate) *)
(* INPUT:     angle --- joint angles in degree away *)
(*            from the robot home position       *)
(*            end_speed --- translational and   *)
(*            rotational velocities of the      *)
(*            end effector                      *)
(* OUTPUT:    ang_rate --- joint rates in degree per *)
(*            second                           *)
(* ******************************************************)

{******************************************************}
type
array4 = array[1..4] of real;
array6 = array[1..6] of real;

var
  angle:  array4;
  ang_rate: array4;
  end_speed: array6;
  b1, b2, b3, b4, b5: real;

const
  pi = 3.1416;
  l = 1.27;
  m = 1.27;
  n = 1.02;
  bz = 0.61;
begin
  b1 := angle[1]\cdot \pi/180.00;
  b2 := (angle[2] - 90.00)\cdot \pi/180.00;
  b3 := (angle[3] + 90.00)\cdot \pi/180.00;
  b4 := b3 - b2;
  b5 := angle[4]\cdot \pi/180.00;
  ang_rate[1] := 
  \frac{\cos(b1) \cdot \text{end_speed}[2] - \sin(b1) \cdot \text{end_speed}[1]}{(l \cdot \cos(b2) + m \cdot \cos(b2+b3))};
  \text{ang_rate}[2] := 
  \frac{\cos(b1) \cdot \text{end_speed}[1] + \sin(b1) \cdot \text{end_speed}[2] - \sin(b2+b3) / \cos(b2+b3) \cdot \text{end_speed}[3]}{l}
  \frac{\cos(b2) \cdot \sin(b2+b3) / \cos(b2+b3) - \sin(b2))}{
  \text{ang_rate}[3] := 
  \frac{- (l \cdot \cos(b2) + m \cdot \cos(b2+b3) / (m \cdot l \cdot \sin(b3))
  \cdot (\cos(b1) \cdot \text{end_speed}[1] + \sin(b1) \cdot \text{end_speed}[2])
  + (\sin(b2+b3) / (l \cdot \cos(b2) + m \cdot \cos(b2+b3)) - l \cdot \sin(b3)) / m / l / \sin(b3) / \cos(b2+b3)
  \cdot \text{end_speed}[3]};
  \text{ang_rate}[4] := \text{end_speed}[6] - \text{ang_rate}[1];
end; {*[ INVJCB *]}

procedure move_to(angle: array4);
var
  i, j, k: integer;
begin
  c[2] := 50.00;
  c[3] := 45.00;
  for i := 1 to 4 do
    begin
      d[i] := c[i] * angle[i];
      comm := 'chn';
      strwrite(comm, 4, f, i; 1);
      strwrite(comm, f, f, '=', ', d[i]; 5; 0);
      writeln(702, comm)
    end;
repeat
  writeln(702, ' lok 9tol2');
  writeln(702, ' dmp9tol2');
  for k := 1 to 4 do
    begin
      readnumberln(702, pos[k]);
      e[k] := angle[k] - pos[k]
    end;
  writeln(702, ' unl 9tol2');
  until ((abs(e[1]) < 1.20) and (abs(e[2]) < 1.20))
  and ((abs(e[3]) < 1.20) and (abs(e[4]) < 1.20))
end; {*[ MOVE *]}
procedure slowdown;
    begin
        writeln(702, 'scn=1,45');
        writeln(702,'ano21=10');
        writeln(702,'ano31=0');
        writeln(702,'ano41=127');
        writeln(702,'scn=1,12')
    end; (procedure slowdown)

procedure speedup;
    begin
        writeln(702, 'scn=1,45');
        writeln(702,'ano21=65');
        writeln(702,'ano31=30');
        writeln(702,'ano41=95');
        writeln(702,'scn=1,12')
    end; (procedure speedup)

PROCEDURE UNLOAD;

VAR
i: integer;

begin
    sign[1]:= -1.00;
    sign[2]:= 1.00;
    sign[3]:= 1.00;
    sign[4]:= -1.00;
    home[1]:= 0.00;
    home[2]:= 0.00;
    home[3]:= 0.00;
    home[4]:= 0.00;
    angle1[1]:= -21.94;
    angle1[2]:= 24.49;
    angle1[3]:= -11.42;
    angle1[4]:= 111.94;
    angle2[1]:= -21.94;
    angle2[2]:= 25.91;
    angle2[3]:= 1.91;
    angle2[4]:= 111.94;
    angle3[1]:= -7.13;
    angle3[2]:= 21.66;
    angle3[3]:= 6.83;
    angle3[4]:= 97.13;
    angle4[1]:= -7.13;
    angle4[2]:= 20.09;
    angle4[3]:= -6.46;
    angle4[4]:= 97.13;
    left1[1]:= 103.74;
    left1[2]:= 13.64;
    left1[3]:= 15.23;
    left1[4]:= 76.26;
\begin{verbatim}
left2[1] := 103.74;
left2[2] := 27.71;
left2[3] := 30.93;
left2[4] := 76.26;
left3[1] := 92.80;
left3[4] := 87.20;
left4[1] := 92.80;
left4[2] := 26.43;
left4[3] := 32.56;
left4[4] := 87.20;
left5[1] := 92.80;
left5[2] := 26.43;
left5[3] := 32.56;
left5[4] := 87.20;
left6[1] := 81.65;
left6[3] := 32.01;
left6[4] := 98.35;
left7[1] := 71.10;
left7[2] := 15.10;
left7[3] := 13.79;
left7[4] := 108.90;
left8[1] := 71.10;
left8[2] := 28.94;
left8[3] := 29.33;
left8[4] := 108.90;
left9[1] := 61.72;
left9[2] := 19.20;
left9[4] := 118.28;
left10[1] := 61.72;
left10[2] := 32.48;
left10[3] := 24.56;
left10[4] := 118.28;
left11[1] := 53.73;
left11[3] := 3.45;
left11[4] := 126.27;
left12[1] := 53.73;
left12[2] := 37.00;
left12[3] := 18.00;
left12[4] := 126.27;
for i := 1 to 4 do
    begin
        angle5[i] := sign[i]*angle1[i];
        angle6[i] := sign[i]*angle2[i];
        angle7[i] := sign[i]*angle3[i];
        angle8[i] := sign[i]*angle4[i];
        right1[i] := sign[i]*left1[i];
        right2[i] := sign[i]*left2[i];
    end
\end{verbatim}
right3[i] := sign[i]*left3[i];
right4[i] := sign[i]*left4[i];
right5[i] := sign[i]*left5[i];
right6[i] := sign[i]*left6[i];
right7[i] := sign[i]*left7[i];
right8[i] := sign[i]*left8[i];
right9[i] := sign[i]*left9[i];
right10[i] := sign[i]*left10[i];
right11[i] := sign[i]*left11[i];
right12[i] := sign[i]*left12[i];

end;
writestringln(702, 'scn=1,12');
writestringln(702, 'bit8=0');
writestringln(702, 'bit9=0');
moveto(home);
writestringln(1, 'Robot Cycle Time in second:');
writestring(1, '1st cycle, left : ');
timel := sysclock;
moveto(angle1);
moveto(angle2);
moveto(angle3);
moveto(angle4);
moveto(left3);
moveto(left4);
moveto(left6);
moveto(left5);
moveto(angle6);
dtime := (sysclock - timel)/100.0;
strwrite(stime,l,f, dtime:5:2);
writestringln(1, stime);
writestring(1, '1st cycle, right : ');
timel := sysclock;
moveto(angle7);
moveto(angle8);
moveto(right3);
moveto(right4);
moveto(right6);
moveto(right5);
moveto(angle2);
dtime := (sysclock - timel)/100.0;
strwrite(stime,l,f, dtime:5:2);
writestringln(1, stime);
writestring(1, '2nd cycle, left : ');
timel := sysclock;
moveto(angle3);
moveto(angle4);
moveto(left5);
moveto(left6);
moveto(left8);
moveto(left7);
moveto(angle6);
dtime := (sysclock - timel)/100.0;
strftime(stime,1,f,dtime:5:2);
writestringln(1, stime);
writestring(1, '2nd cycle, right : ');  
time1:= sysclock;
move_to(angle7);
move_to(angle8);
move_to(right5);
move_to(right6);
move_to(right8);
move_to(right7);
move_to(angle2);
dtime:= (sysclock - time1)/100.0;
strftime(stime,1,f,dtime:5:2);
writestringln(1, stime);
writestring(1, '3rd cycle, left : ');  
time1:= sysclock;
move_to(angle3);
move_to(angle4);
move_to(left7);
move_to(left8);
move_to(left10);
move_to(left9);
move_to(angle6);
dtime:= (sysclock - time1)/100.0;
strftime(stime,1,f,dtime:5:2);
writestringln(1, stime);
writestring(1, '3rd cycle, right : ');  
time1:= sysclock;
move_to(angle7);
move_to(angle8);
move_to(right7);
move_to(right8);
move_to(right10);
move_to(right9);
move_to(angle2);
dtime:= (sysclock - time1)/100.0;
strftime(stime,1,f,dtime:5:2);
writestringln(1, stime);
moveto(angles);
moveto(home);
end; {* UNLOAD *}

PROCEDURE LOAD;

VAR
  i: integer;

begin
  sign[1]:= -1.00;
  

sign[2] := 1.00;
sign[3] := 1.00;
sign[4] := -1.00;
home[1] := 0.00;
home[2] := 0.00;
home[3] := 0.00;
home[4] := 0.00;
angle1[1] := -24.94;
angle1[4] := 114.94;
angle2[1] := -24.94;
angle2[2] := 25.91;
angle2[3] := 2.31;
angle2[4] := 114.94;
angle3[1] := -7.65;
angle4[1] := -7.65;
angle4[3] := -6.34;
angle7[1] := 8.17;
angle7[3] := 7.58;
angle7[4] := -98.00;
angle8[1] := 8.17;
angle8[3] := -6.63;
angle8[4] := -98.00;

left1[1] := 103.74;
left1[2] := 13.64;
left1[3] := 15.23;
left1[4] := 76.26;
left2[1] := 103.74;
left2[2] := 27.71;
left2[3] := 30.93;
left2[4] := 76.26;
left3[1] := 92.80;
left3[4] := 87.20;
left4[1] := 92.80;
left4[2] := 26.43;
left4[3] := 32.56;
left4[4] := 87.20;
left5[1] := 81.65;
left5[2] := 12.64;
left5[4] := 98.35;
left6[1] := 81.65;
for i:=1 to 4 do 
begin
angle5[i]:= sign[i]*angle1[i];
angle6[i]:= sign[i]*angle2[i];
right1[i]:= sign[i]*left1[i];
right2[i]:= sign[i]*left2[i];
right3[i]:= sign[i]*left3[i];
right4[i]:= sign[i]*left4[i];
right5[i]:= sign[i]*left5[i];
right6[i]:= sign[i]*left6[i];
right7[i]:= sign[i]*left7[i];
right8[i]:= sign[i]*left8[i];
right9[i]:= sign[i]*left9[i];
right10[i]:= sign[i]*left10[i];
right11[i]:= sign[i]*left11[i];
right12[i]:= sign[i]*left12[i]
end;
writestringln(702, 'scn=1,12');
writestringln(702, 'bit8=0');
writestringln(702, 'bit9=0');
move_to(home);
move_to(left9);
move_to(left10);
move_to(left8);
move_to(left7);
slowdown;
moveto(angle4);
speedup;
moveto(angle3);
moveto(angle2);
moveto(right10);
moveto(right8);
moveto(right7);
slowdown;
moveto(angle8);
speedup;
moveto(angle7);
moveto(angle6);
moveto(left8);
moveto(left6);
moveto(left5);
slowdown;
moveto(angle4);
speedup;
moveto(angle3);
moveto(angle2);
moveto(right8);
moveto(right6);
moveto(right5);
slowdown;
moveto(angle8);
speedup;
moveto(angle7);
moveto(angle6);
moveto(left6);
moveto(left4);
moveto(left3);
slowdown;
moveto(angle4);
speedup;
moveto(angle3);
moveto(angle2);
moveto(right6);
moveto(right4);
moveto(right3);
slowdown;
moveto(angle8);
speedup;
moveto(angle7);
moveto(angle6);
moveto(angle5);
moveto(home);
writeln(702, 'bit8=1');
writeln(702, 'bit9=1');
writeln(702, 'scn=1,45')
end; (* LOAD *)
APPENDIX B

SAMPLE EXECUTION DATA OF INVERSE KINEMATICS

<table>
<thead>
<tr>
<th>JOINT 1 (degree)</th>
<th>JOINT 2 (degree)</th>
<th>JOINT 3 (degree)</th>
<th>JOINT 4 (degree)</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.26267E+02,2.46094E+01,3.45051E+00,-1.2627E+02,LIMIT EXCEEDED</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.26267E+02,3.64210E+01,1.76972E+01,-1.2627E+02,LIMIT EXCEEDED</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.18282E+02,3.18981E+01,2.41601E+01,-1.1828E+02,VALID SOLUTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.18282E+02,1.92024E+01,9.52551E+00,-1.1828E+02,VALID SOLUTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.08901E+02,1.50951E+01,1.37914E+01,-1.0890E+02,VALID SOLUTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.08901E+02,2.84407E+01,2.88284E+01,-1.0890E+02,VALID SOLUTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.83479E+01,2.63624E+01,3.15127E+01,-9.8348E+01,VALID SOLUTION</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.83479E+01,1.26429E+01,1.61938E+01,-9.8348E+01,VALID SOLUTION</td>
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<td></td>
<td></td>
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<tr>
<td>8.71998E+01,1.21352E+01,1.66777E+01,-8.7200E+01,VALID SOLUTION</td>
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<tr>
<td>8.71998E+01,2.59304E+01,3.20587E+01,-8.7200E+01,VALID SOLUTION</td>
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<tr>
<td>7.62573E+01,2.72093E+01,3.04302E+01,-7.6257E+01,VALID SOLUTION</td>
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<tr>
<td>7.61652E+01,1.36404E+01,1.52296E+01,-7.6257E+01,VALID SOLUTION</td>
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<tr>
<td>6.62401E+01,1.69646E+01,1.18873E+01,-6.6240E+01,VALID SOLUTION</td>
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<tr>
<td>6.62401E+01,3.00174E+01,2.67301E+01,-6.6240E+01,VALID SOLUTION</td>
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<tr>
<td>1.13760E+02,3.00174E+01,2.67301E+01,6.62401E+01,VALID SOLUTION</td>
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<tr>
<td>1.13760E+02,3.00174E+01,2.67301E+01,6.62401E+01,VALID SOLUTION</td>
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<td>1.03743E+02,1.36404E+01,1.52296E+01,7.62573E+01,VALID SOLUTION</td>
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<td>9.28002E+01,1.21352E+01,1.66777E+01,8.71998E+01,VALID SOLUTION</td>
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<tr>
<td>9.28002E+01,2.59304E+01,3.20587E+01,8.71998E+01,VALID SOLUTION</td>
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<tr>
<td>8.16521E+01,2.63624E+01,3.15127E+01,9.83479E+01,VALID SOLUTION</td>
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<tr>
<td>8.16521E+01,1.26429E+01,1.61938E+01,9.83479E+01,VALID SOLUTION</td>
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</tr>
<tr>
<td>7.10993E+01,1.50951E+01,1.37914E+01,1.08901E+02,VALID SOLUTION</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>7.10993E+01,2.84407E+01,2.88284E+01,1.08901E+02,VALID SOLUTION</td>
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<tr>
<td>6.71719E+01,3.18981E+01,2.41601E+01,1.18282E+02,VALID SOLUTION</td>
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<tr>
<td>6.17179E+01,1.92024E+01,9.52551E+00,1.18282E+02,VALID SOLUTION</td>
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<tr>
<td>5.37327E+01,2.46094E+01,3.45051E+00,1.26267E+02,VALID SOLUTION</td>
<td></td>
<td></td>
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<tr>
<td>5.37327E+01,3.64210E+01,1.76972E+01,1.26267E+02,VALID SOLUTION</td>
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<tr>
<td>2.19385E+01,2.59091E+01,1.91325E+00,-1.1194E+02,VALID SOLUTION</td>
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<td>2.19385E+01,1.91325E+00,1.1194E+02,VALID SOLUTION</td>
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<tr>
<td>8.16521E+01,6.66053E+00,-9.8167E+01,VALID SOLUTION</td>
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APPENDIX C

MODIFIED MOVE_TO PROCEDURE

procedure MOVE_TO(angle: array4);

var
  i: integer;
  j: integer;
  k: integer;

begin
  c[2] := 50.00;
  c[3] := 45.00;
  for i := 1 to 4 do
    begin
      d[i] := c[i] * angle[i];
      comm := 'chn';
      strwrite(comm, 4, f, i:1);
      strwrite(comm, f, f, '='; d[i]:5:0);
      writeln(printout, ' New Step');
    end;
  writeln(printout, 'lok 9 to 12');
  timel := sysclock;
  writeln(printout, 'dmp 9 to 12');
  for k := 1 to 4 do
    begin
      readnumberln(702, posl[k]);
      vel1[k] := 0.0
    end;
  writeln(printout, 'unl 9 to 12');
  repeat
    time := sysclock - timel;
    if time < 20 then
      begin
        waittime := sysclock + 20 - time;
        while sysclock < waittime do;
      end;
    dtime := sysclock - timel;
    writeln(printout, 'lok 9to12');
    timel := sysclock;
    writeln(printout, 'dmp9to12');
    for k := 1 to 4 do
      begin
        writestringln(702, comm)
      end;
end;
readnumberln(702, pos[k]);
e[k] := angle[k] - pos[k];
vel[k] := 100.0*(pos[k] - posl[k])/dtime;
acc[k] := 100.0*(vel[k] - vell[k])/dtime;
posl[k] := pos[k];
vell[k] := vel[k];
writeln(printout, dtime, ' ', pos[k], ' ', vel[k], 
' ', acc[k]);
write(dataout, dtime, pos[k], vel[k], acc[k])
end;
writeln(printout, ' ');
writestringln(702, 'unl 9to12');
until ((abs(e[1])<1.50) and (abs(e[2])<1.50))
and ((abs(e[3])<1.50) and (abs(e[4])<1.50))
end;
### APPENDIX D

**SAMPLE DATA OF ROBOT JOINT POSITION, VELOCITY, AND ACCELERATION**

<table>
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<tr>
<th>JOINT INTERVAL (centi-second)</th>
<th>JOINT POSITION (deg)</th>
<th>JOINT VELOCITY (deg/sec)</th>
<th>JOINT ACCELERATION (deg/sec^2)</th>
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### APPENDIX E

**SAMPLE DATA OF END EFFECTOR VELOCITY AND ACCELERATION**

Unit: $v \text{ --- m/s}$  
$a \text{ --- m/s}^2$

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<th>Z component</th>
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<td>$a$</td>
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