Proceedings of the 2002 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
EPFL, Lausanne, Switzerland • October 2002

Junior: A Robot for Outdoor Container Nurseries

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Abstract

Production of nursery crops in the US is accomplished in container- and field-growing conditions, with propagation and seedling-rearing carried out in greenhouses; 11% of the US national farm-product is represented by these crops. Container-grown crops represent 60% of the US market and represent a highly labor-intensive and thus costly segment of ornamental crop production. The USDA, NASA and the ANLA have collaborated to develop an automated in-field container-handling system for reducing dependence on foreign labor while also increasing productivity. A prototype system was developed at CMU, capable of automatically lifting and conveying plants from the ground (in a variety of regular patterns) onto trailers, and vice-versa. The system is capable of handling a vast array of container-designs from different manufacturers, and spans the size-range from #1 to #3 (approximate equivalence to US gallons). The system is designed to handle 35,000 containers per 8-hour day with one to two operators. Field-trials currently underway has shown the system to reliably handle 29,000 #1 containers per 8-hour day with less than a 3% failure-rate. Testing in various growth-zones and surfaces is underway, with commercialization efforts in Europe/US.

1. Industry Overview

US ornamental horticulture is a rapidly growing, $11 billion dollar a year industry (about 11% of the gross agricultural output of the US alone), tied to a dwindling migrant work force, working in outdoor conditions in very large acreage areas (see Figure 1).

Unskilled labor is becoming more costly and harder to find, while it is still needed to move potted plants - this represents a manual handling task of at least 450 million units per year, each handled 3 to 4 times a year. The US nursery industry must address this problem if it is to survive and continue to flourish in the millennium.

Nursery production automation is a growing field worldwide. At the highest level there are three main areas, namely greenhouse operations, container yards and field nurseries. Within these groupings, there are several areas that lend themselves to automation (see Table 1):

***Figure 1** : Typical container nursery view & labor task*

***Table 1** : Automation Areas for Nursery Industry*

AREA	AUTOMATION-FRIENDLY
Greenhouse	*Seed/Propagate, Pick/Ship, Gather, Transplant/Set*
Container Yard	*Field Movement, Upshifting, Order-Picking, Shipping*
Field Nursery	*Dig, Plant, Stake, Harvest, Container Handling*

In these areas it was judged [2] that automation has achieved different levels of automation-penetration worldwide (see levels in histogram shown in Figure 2).

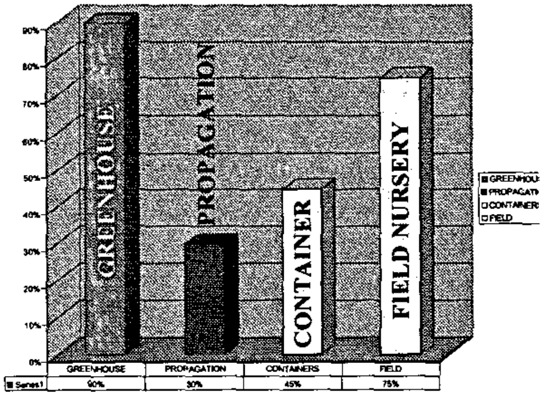

***Figure 2** : Automation Levels in Nursery Industry*

2. Performance Requirements

The motivation to automate being obvious, it becomes important to realize that the US market has a high affinity to price and performance. The performance requirements that were derived for the proposed container-handling system, focussed around several key areas, namely (i) throughput (containers/day), (ii) applicability to existing infrastructure (containers, groundcover), (iii) compatibility with existing equipment (trailers, cold-frames), (iv) manpower reduction, (v) job-quality (compared to manual), and (vi) cost-effectiveness (ROI-based). The system has to be able to pick-up and drop-off in can-to-can and can-tight, as well as diamond-spaced configurations, and do so at a rate to pay back for the system in terms of labor-savings within as few seasons as possible. Performance variables and the expected value for each are shown in Table 2.

3. System Description

The design developed for the automated field-container handling system represents a self-mobile outdoor platform powered by an IC engine, perceiving containers through a laser range-finder, controlled through an on-board PLC computer, and actuated through a set of electro-hydraulic and electro-mechanical actuation systems. A CAD image of the developed prototype system is shown in Figure 3.

Junior relies on an electrically-driven, differentially-steered, forward drivetrain with rear floating rocker-arm with passive casters. The overall frame-structure supports an IC engine powering a generator, providing all electrical power and driving a small hydraulic pump. Containers are picked up/dropped onto the ground row-by-row using a hydraulically-powered squeeze-pinch grabber-bar (for a 7-foot wide bed), which is fine-positioned by a XYθ-head sitting on a curvilinear carriage to provide for coarse motions (extend/retract, raise/lower and rotate CW/CCW).

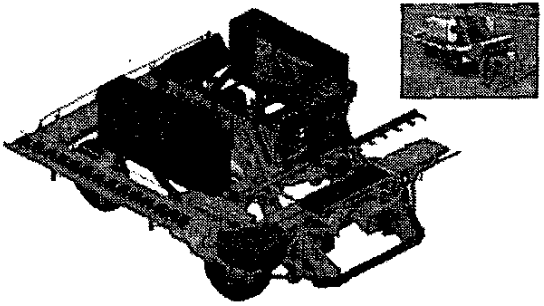

***Figure 3** : Junior: System prototype - CAD & Inset*

Conveyors rapidly move containers off to the side (onto a waiting trailer); the operation is run in reverse for setting down and spacing out containers.

All driving and grabber-alignment functions are based on the 2D laser imaging data from a front-mounted all-weather SICK laser. The overall system can thus be seen to consist of several major elements, including (i) frame, (ii) drive & steer, (iii) container grabber & handler, (iv), and power & control systems. The roles and interconnections of each of the above modules can be generically described as detailed below:

The frame consist of a welded tubular structure, upon which rest the IC power-plant, hydraulic drive system, power and control electronics, as well as the container grabbing and handling unit and its associated conveyors. The system was oversized so as to allow for laboratory testing of all possibly useful features, which are then to be evaluated for inclusion in the commercial

DESCRIPTOR	TARGET	VALUE
Containers moved in the field per hour	*Meet/Exceed 4-person daily rate*	***25,000/day[a]***
System Design	*Stand-alone System*	***N/A***
Trailer Compatibility	*Compatible with typical trailer*	***4' x 10'***
Operator Reduction	*Single-operator for system*	***1 Operator***
Quality and Control Assurance	*No extra plant/container damage*	***N/A***
Multi-container usability	*Adaptable[b] to #1, #2, # 3*	***Yes***
Container Configurations	*Can-to-Can, Can-tight, Spaced[c]*	***Yes[c]***
Multi-surface operability	*Gravel, Geotextile - NO Poly!*	***Yes***
Cold-Frame Compatibility	*Access into/sideways frames*	***Yes[d]***
Cost-Effectiveness	*Typical stand-alone system*	***$50K to $75K***

a. Refers to #1 containers in an 8-hour workday with a single operator, or about 2,500 containers/hour!
b. manually adjustable over a range or usage of a different tool-head
c. in a follow on system adapted based on the baseline system

prototype (see Figure 4):

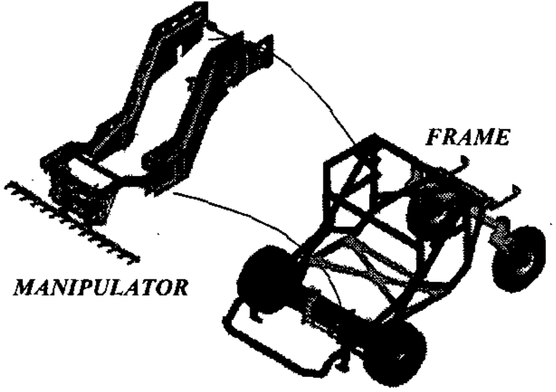

Figure 4 : Frame & Manipulator Assembly

The main power source for the system consists of an internal combustion-engine mounted on the frame, providing both electrical power via a generator, and hydraulic power through a direct-coupled pump. The power is regulated through a dedicated cabinet, while the electronics and controls for the PLC and the relays and valves are housed in a separate compartment. Fuel-tanks and cooling radiators are mounted on the frame as well. A picture of the subsystems is shown in Figure 5:

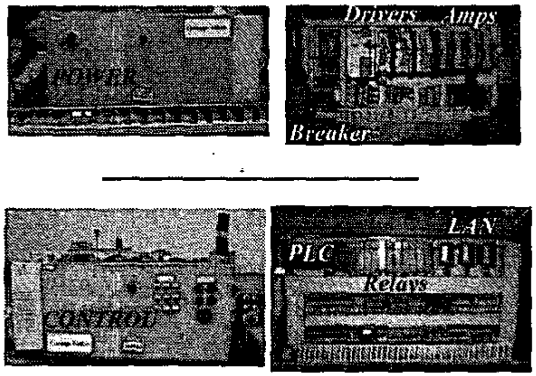

Figure 5 : Power & Control Subsystem Enclosures

The locomotion unit consists of a front-mounted drive-tube with two DC motor driven gearboxes on either end, coupled to low-pressure turf-tires by way of a manual splined hub (allowing high-speed towing by decoupling the drivetrain from the wheels). The drive and steering for the machine is achieved by driving the two front wheels in a differential manner. The system was thus capable of an in-place turn about the center of the front axle, which was essential for operating within the plant-bed to minimize wasted motions and optimally combine gross (vehicle-base) and fine (grabber-head - detailed next) motions.

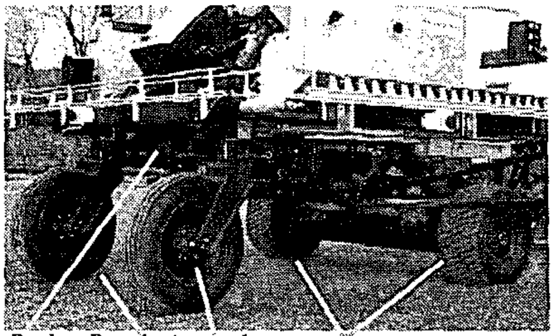

Figure 6 : Locomotion and Steering Subsystems

The method used to grab containers reliably, without requiring any specialized container design (Europe has standardized containers, simplifying handling equipment design), is based on an articulated double half-moon friction-clamp design. By ganging these pinch-grabbers along an actuated rail (push/pull linkages to open/close clampers), a whole row of containers can be grabbed at once and moved around. The bar-mounted pinch-grabber is mounted to the articulated XYθ-positioner-head that rides on the translating carriage. This 'head' allows the machine to fine-position the grabber-bar to align with the row of containers on the ground for pickup/drop-off. This method allows for the large variations in displacements and alignments of containers on the ground, even if placed by hand (seeFigure 7).

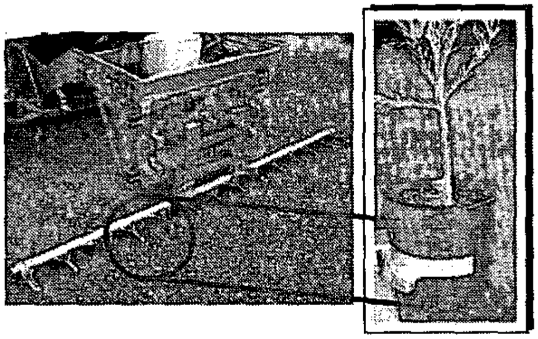

Figure 7 : Grabber-Bar & XYθ*–Positioner Head*

In order to perform up-close positioning of the grabber-head so as to achieve 'proper' alignment with the containers for a full-row pick-up, despite the potential misalignment of the vehicle and grabber system itself, the misplacement of containers, etc., requires the use of an integrated sensing system. A system was designed that meets these requirements, based on the testing results of several candidate sensors. The system utilizes a 2-D Infrared laser scanner manufactured by SICK, Inc. (i.e. LMS-200). This laser was selected based on its superior performance under such worst case situations where the sun was low, the pots were on snow, and the laser was in line of sight with the sun (i.e. no shadows); this laser scanner reliably sees pots in these extreme conditions.

The sensory system used to control the machine-heading, grabber-bar and XYθ-positioner and pincher open-close states, is based on the processing of range-measurements from the SICK planar laser-scanner system. The laser range measurements from the SICK taken in the field (see Figure 8 for point-cloud data with superimposed cylinder-location estimates from post-processing) are post-processed to obtain the line and orientation of the container-row on the ground (see Figure 9), the vehicle heading (coarse-motions) and the grabber-orientation (fine motion).

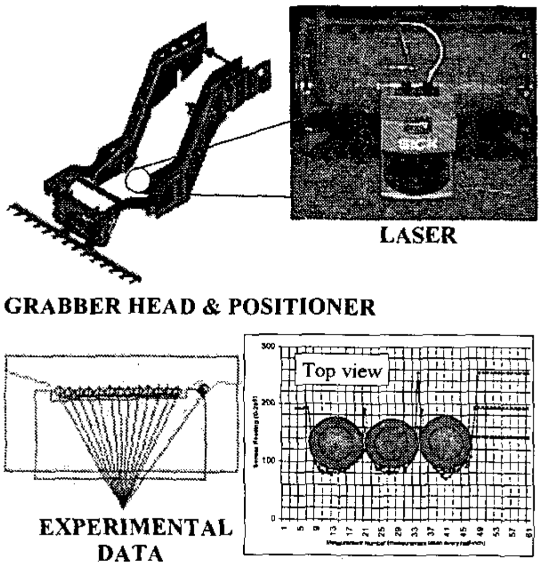

Figure 8 : Container Grabber, Scanner & Data

The sensor interpretation algorithm performs a variety of calculations. First, the number of data points is reduced to include only relevant data as defined by the larger rectangle. Next, the raw data is analyzed to determine where it sees shapes that look like pots, after which the position of these pots is determined. A best fit line is then calculated for the group of pots (i.e. X, Y and θ values). Position of each of these pots are checked to determine if they are within range and tolerance for successful pickup by the grabber head. Additional checks are made to determine if any obstacles are detected in the small irregular shaped polygon in Figure 8. All of this information is used to control the coarse movements of the vehicle and the fine movements of the grabber head. Additionally, the laser can be programmed to monitor taught areas and indicate (i.e. via discrete outputs) when obstacles are present in each of these areas. This feature is used for safety monitoring to ensure that the carriage does not move from conveyor → ground or ground → conveyor positions unless these areas are clear obstacles and persons. The sensor interpretation algorithm was written in C and runs on a special-purpose PLC module with two serial interface ports, utilizing a 386 processor. All data is transferred to this special purpose PLC module via an RS-232 serial interface.

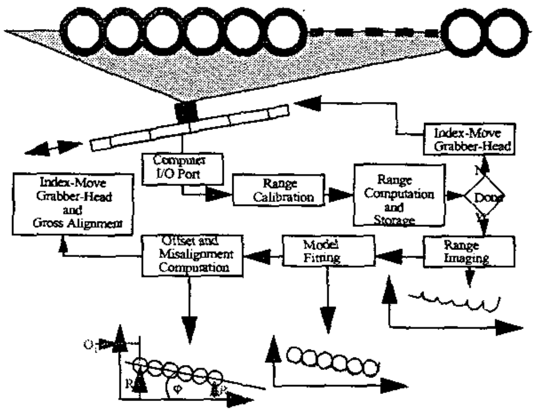

Figure 9 : Software Sensor-Control Diagram

The electronics and control system is based on commercial off-the-shelf industrial automation hardware. A high-level hardware architecture is shown in Figure 10. The control system is based on Allen-Bradley's SLC-500 line of programmable logic controllers (PLC). The PLC is housed in a ten-slot chassis with a CPU (SLC 5/05) and a variety of I/O cards including: discrete I/O (6 cards), analog I/O (2 cards), application development module (1 card – 386 CPU).

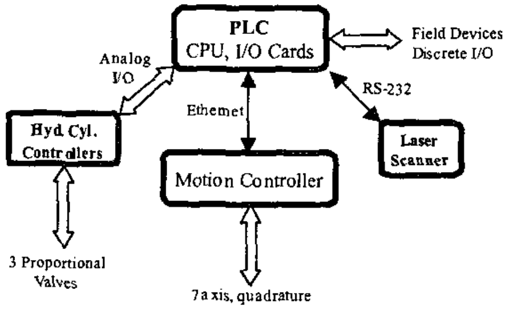

Figure 10 :High-Level Electronics Architecture

The discrete I/O modules are used for input from switches, push buttons, proximity sensors and IR switches and output to solenoid valves, relays, motor starters and indicator lights. The analog I/O is dedicated to the control of hydraulic cylinders that control the fine position and orientation of grabber head. The motion controller provides precise position or velocity control of the following axes: drive wheels (2), conveyors (3), carriage (1) and indexer (1). The system Operator will interact and control the system via buttons, switches and a joystick. The operator interface was designed and modeled after industrial automation that would be operated by a low-skill workforce. Hence, a computer monitor and keyboard are not required to control and operate the system.

The control logic for the robot was implemented using Programmable Logic Controller (PLC) ladder logic and the associated hardware. The ladder logic was written in a modular systematic manner. This enables more efficient commissioning and maintenance of system software. The program consists of a main program, device control, input references, output references and several processes. The main program provides overall control. The device control is the only place where physical devices are controlled (.e.g. motors, valves, cylinders). The input and output references map all internal software variables to the real world I/O hardware. The processes are where the majority of all control logic and all control sequences are implemented. This software architecture is shown in Figure 11..

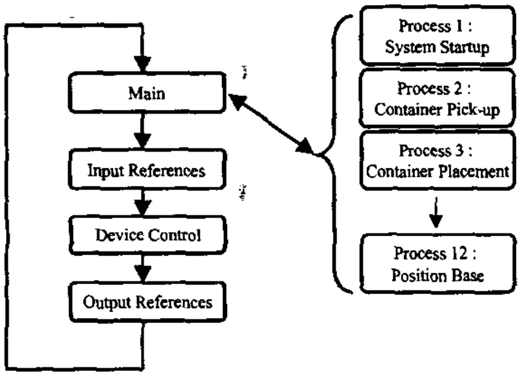

Figure 11 : Software Architecture Layout

Movement of the base system via the drive wheels is rather straightforward for both pick-up and placement of containers. In both of these cases, the grabber head makes all of the fine motions and the base provides coarse/basic moves. For container placement operations, the base makes simple dead reckoned moves based on the type of container placing-scheme chosen by the operator (e.g. can-tight, can-to-can). In order to maintain a consistently straight set-down path, the operator will occasionally have to pause the process and make minor vehicle heading corrections. For container pick-up operations, the base motion uses the 2D laser data and operator-selected container-configuration to guide the system. The first move the base makes is a dead-reckoned move, all subsequent moves are based on the 2D laser data. Heading and lateral corrections of the base are only made if the angular correction and lateral correction is above a threshold. This was done in order maximize system productivity and only these corrections when the grabber head may not be able to correct for the variations. This navigation approach is shown in Figure 12.

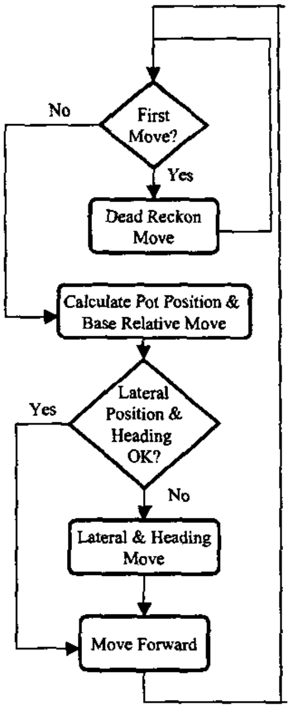

Figure 12 : Handling Flow-Chart Diagram

4. Field Testing

A fully assembled locomotion platform of the container handling system is shown in Figure 13 during locomotion trials on the experimental nursery at CMU's NREC experimental nursery. The systems' performance was measured over a 7-foot wide and 50 foot long bed using a variety of #1 containers and different plant-types and weights (see Figure 14). Initial testing indicates that the sensing scheme was able to position the system accurately enough (to within 0.01m), with closed-loop speeds enabling a productivity of about 31,000 #1 containers per 8-hour day in a field setting. The cycle-time per 13-container row hovered around the 14-second mark, depending on the amount of vehicle positioning corrections (3 seconds conveyor unloading, 7 seconds of carriage motion, 2 seconds of grabber/ grabber head motions and 2 seconds of miscellaneous dwells).

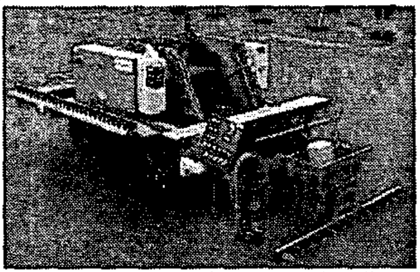

Figure 13 : Fully integrated container handling system

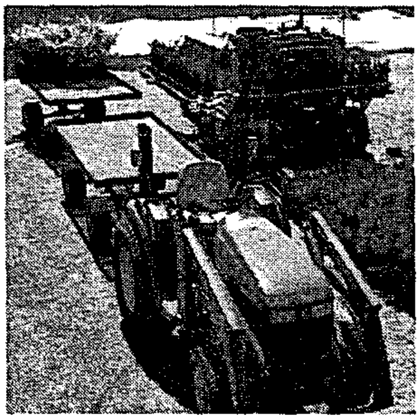

Figure 14 : Test-nursery field-trial setting

Containers from 7 different manufacturers with varied plants (from tall to broad) were successfully handled without dropping or losing grip. Safety-scanning settings for the laser proved to work in terms of tipped-over cans and other obstacles in the way. Productivity in the collapsed cold-frame operating mode with an indexing head were far slower (5x) due to the need to properly space the cans onto the conveyor during set-down. Groundcovers ranging from gravel to sand to woven plastic were shown to be handled well by the machine without tearing or rutting the soil. The operator interface was found to be simple enough to use, even when manual reset and resumption of automated handling was required. Initially three operators were needed to load/unload (2 operators) and oversee the machine (1 operator) - after multiple hours, the machine operator duties were taken over by one of the loader operators, making the system operable by two people.

5. Summary & Conclusions

The container handling system presented herein represents a major step towards automation of labor-intensive container-handling tasks in medium to large-sized container nurseries in the US. The system represents a new class of smart outdoor automation systems utilizing existing hard-automation components, aided by smart sensors, intelligent software and innovative mechanism design. Testing of the system has shown its capability to achieve the productivity of 18,000 to 20,000 #1 containers per day (See Table 3) with up to two operators, without regard to the type of hauling-trailer. The system is capable of handling a large variety of containers available through US manufacturers. Groundcovers suitable for the machine and tested to date, include gravel and woven groundcover. The system will undergo additional field-trials in the US in mid-2002 prior to commercialization.

6. Acknowledgements

The container handling system was jointly funded at Carnegie Mellon University (CMU), by NASA under research-grant #NCC5-223, the US Dept. of Agricultures' (USDA) Agricultural Research Office (ARS) under a SCA (#58-1230-8-101/58-3607-0-130), and a grant from the Horticultural Research Institute (#1999-128/2000-163). The system and process have both USPTO & PTC patent pending status.

7. References

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***Table 3** : Preliminary Field-Trial Performance Data*

PLACE	ACTION	Setting	Rows	Failures	Time[a]
NURSERY #1	*Set-Down*	5,000 No.1s[b]	Two 2.5 ft. wide rows; 110 ft. long	Dropped Pots: 20 (0.4%)	**PLACE** **20,000 Cans**
	Pick-up	2,400 of same	Same	Dropped Pots: 30 (1.25%)	
NURSERY #2	*Set-Down*	1,200 No.1s[c]	Two 2.5 ft. wide rows; 110 ft. long	Dropped Pots: 14 (1.1%)	**PICK-UP** **18,000 Cans**
	Pick-up	1,200 of same	Same	Dropped Pots: 28(2.3%)	

a. Based on 8-hour work-day with two (2) 15-minute breaks and 13-second cycle-time

b. Freshly potted boxwoods; Injection-molded containers

c. 2-month since potting; blow-molded containers