TRIDENT SENSING SYSTEM: A CONFIGURATION OF SENSORS TO AID ALIGNMENT OF AN INTELLIGENT GRASPING DEVICE USED FOR FIELD-CONTAINER HANDLING

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Abstract

The nursery industry faces an impending crisis due to lack of labor resources. A majority of the manual labor in container nurseries involves moving containers from the field to other locations and back. Typically 3-4 laborers team up to load the containers onto trailers and then drive them to the required destination where they are unloaded. The Trident system was designed to automate some aspects of this process by enabling a single operator to load and unload containers into and from trailers while matching the performance of the 4-laborer teams. This report highlights the mechanical details of the Trident system experimental prototype built at Carnegie Mellon University, and examines the requirements of a suitable sensing configuration for the system. The authors propose a specific configuration of GP2D02 sensors as a candidate for Trident's sensing system. Results of initial experimentation to evaluate the suitability of the GP2D02 sensors are presented along with a description and performance analysis of a sensing system prototype that was built using these sensors. Initial performance of the sensing-system prototype promotes the GP2D02 as a strong candidate for fulfilling Trident's sensing-system requirements, although some difficulties may arise with the active range of the sensors. The recently released GP2D12 promises to be a stronger candidate for the sensor of choice since it could potentially overcome some of the difficulties posed by its predecessor, the GP2D02.

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Acknowledgements

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[1] No. 58-1230-8-101

Trident Sensing System

Introduction

Trident was envisioned as an intelligent grasping device that would automate the task of field-container handling in outdoor nurseries. Preferably, the device would interface with a tractor (a common prime mover in the nursery industry), and require only a single human operator to transfer a trailer load of potted plants from the nursery beds to a re-potting (or other) location; a task that would traditionally require up to 3-4 humans (2-3 to load the trailer and 1 to drive the tractor). This project envisions Trident enabling a single, skilled operator to align the prime mover with a bed of containers, and transfer the containers from the bed to the trailer in an automated, less expensive (long-term), and more efficient manner.

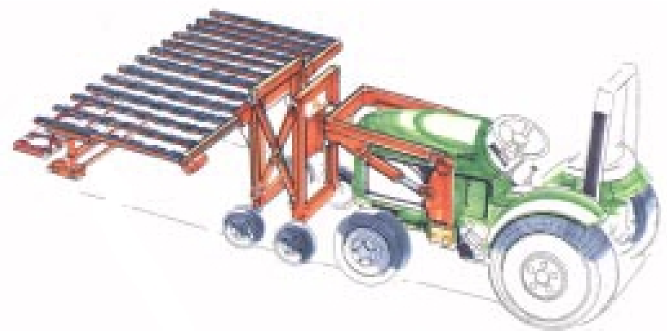


Figure 1: Illustration of Trident interfaced with a prime mover

The Trident project was motivated by the impending labor crisis in the nursery industry. While high school students used to be the primary candidates for field container handling (since 80% of the turnover in the nursery industry occurs in the summer time), they now have many more attractive job offers for more skilled and less physically demanding work. Hence, the only labor available to the nursery industry (i.e. those who are willing to work in the field all day lifting heavy pots) are migrant workers from Mexico and South America, hired on a seasonal basis. The procedure for hiring these laborers is becoming more and more difficult, requiring continued lobbying in Washington, DC to guarantee exemptions from the INS. In addition, high costs are incurred to carry out recruiting across the border, providing transportation for laborers to and from their hometowns, and providing these laborers accommodation while they work in the US. Furthermore, the nursery industry is facing stiff competition for the same labor pool from industries that require labor for tasks such as assembly and custodial work – jobs with less strenuous work and hence, more attractive to the laborers. Thus, it is hoped that Trident will not only make the task of loading and unloading containers more efficient, but will also make the operator's task less physically demanding, and thereby more attractive to the laborers, by accomplishing the more tedious and hard labor autonomously. While Trident will rely on the human operator for gross alignment with the rows of containers, the fine alignment in 3 dimensions (x, y, and θ) will be carried out by an intelligent grasping head whose control system will use a configuration of sensors to guide accurate alignment with the containers. This report outlines the design specifications, software algorithms, and hardware implementation of the initial experimental prototype of the Trident sensing system.

An overview of the nursery and landscape industry is provided next, followed by a description of the task, and a high-level description of Trident. The requirements of the sensing system are then examined, and a summary of the search for appropriate sensors is provided. A detailed description of the chosen sensors, along with a summary of experimental investigations of these sensors, and a description of how they are integrated into the Trident sensing system follows. The report concludes with an analysis of the performance of the Trident sensing system, and an outline of possible enhancements of the system to be carried out in the future.

Overview of Nursery Industry Operations

The nursery industry supplies ornamental crops to landscaping and garden centers where consumers and landscapers can acquire plants for planting in consumer's yards and in their homes and offices. The plants are grown and nurtured to a sufficiently matured stage in large nurseries (see Figure 2). These ornamental plants and shrubs

Figure 2: Typical outdoor nursery growing bed setup

represent approximately $10.9 billion (as much as 11% of the national cash-receipts for all US crops) in farmgate value, according to the USDA. Thus, the nursery industry in the US, a multi-billion dollar industry with more than 2000 nurseries distributed nationwide, has grown by 50% in the last 25 years while all other agricultural sectors have steadily declined. Plants grown in nurseries can be segregated into two groups; shrubs and trees. While trees are grown in the ground, shrubs are grown almost exclusively in containers (mainly plastic) and represent approximately 60% of the nursery industry. It is estimated that nearly 2.2 billion containers are used annually to grow plants for resale to nurseries, garden centers, landscapers, and ultimately consumers. (This figure is based on extrapolation from data provided by the American Nursery and Landscape Association).

Container nurseries vary widely in size. The small mom-and-pop outfits can be as small as 15 to 30 acres whereas the bigger nurseries can be split up into multiple sites covering hundreds or even thousands of acres in total. Container nurseries also vary in geographical location, and thereby are affected by different growing climates and seasons. In the cold regions, plants are grown in over-wintering structures (see Figure 3) which provide warmth to

Figure 3: Over-wintering structures in a container-nursery

the plants in the cold seasons by preventing the cold air from seeping through their plastic-sheet walls. In the hot season, the plastic walls are rolled up or removed, thus preventing overheating of the plants. In the warmer regions, containers are laid out in the field for the most part. Therefore, in order to move the containers either to the re-potting sheds or to the loading docks, one must be able to move in and out of the over-wintering structures in the cold regions, and to move around the fields in the warm regions. The majority of labor-intensive tasks in container-nurseries involves handling containers; primarily, moving containers into and out of trucks and trailers. Even though the container-nurseries come in a variety of shapes and sizes, most of them share a basic set of manual container handling operations.

Figure 4: Manual container handling operations in a container-nursery

Containers are typically re-potted before every growing season. This requires the containers to be picked up in the field or from the over-wintering structures, loaded onto trailers, driven to a canning shed where they are re-potted in larger containers, placed back on trailers, driven back to the fields, and set down in the field sufficiently spaced to allow the plants to grow. Depending on the season, the containers can be placed in different configurations in the growing beds; in the cold weather they are placed in a can-to-can configuration (see Figure 5 - a) or a can-tight configuration (see Figure 5 – b) in order to maximize warmth, while in the hotter seasons they are placed in a spaced configuration to allow growth. Thus, picking up and setting down containers in all of these configurations must be possible. In addition, different nurseries have different ground-cover materials in their growing beds (for example, some nurseries spread granite in their growing beds while others spread plastic ground covering sheets) which complicates the task of gaining access to the containers in the growing beds. Moreover, many of the over-wintering structures and growing beds are fitted with irrigation systems which have some combination of pipes, tubing, and sprinklers mounted at different points which also add to the complexity of accessing the containers. In the retail season, the continued shipping schedule requires additional labor to select plants to fill orders, transport the selected plants to the shipping docks, and load them onto trailers. Nurseries in cold regions also require laborers to move all the plants into the over-wintering structures during the winter season. All of these tasks are extremely labor intensive, and hence labor costs tend to amount to between 20% and 60% (with an average of approximately 50%) of revenue in most container-nurseries.

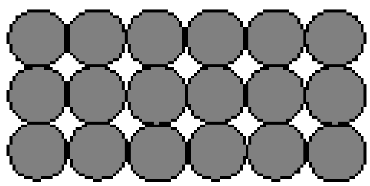


Figure 5 – a: Can-to-can configuration

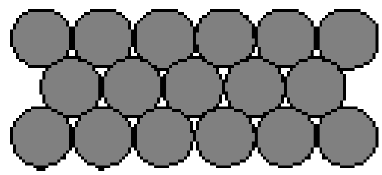


Figure 5 – b: Can-tight configuration

Description of Automation Task

The focus of the Trident project was to develop an automated system to perform pick-up and drop-off of containers (in can-to-can and can-tight configurations) in an efficient and cost effective manner. The automated system needed to at least match the efficiency, long-term cost, and performance of the currently employed laborers, and preferably decrease costs while increasing efficiency. Furthermore, the design process was geared towards an automated system that would be amenable to the largest number of growers possible. This meant taking into account nurseries of various sizes, different forms of over-wintering structures, different ground-cover materials, various space allocations, numerous prime movers, and budgetary constraints. It is clear that any product developed will not be suitable for use in all nurseries. Hence, in order to develop a reliable system that would work efficiently and be cost effective, several compromises had to be made in the design of Trident. These compromises are documented in the next section.

The project was structured into a two-phase program. The first phase focused on the development of feasible concepts, the analysis of cost-benefit figures, the testing of pre-prototype solutions, and building the final prototype, within a twelve month duration. The second phase, spanning 12 – 18 months, will focus on building and testing the final design prototype system, and carrying out extensive field-trials at various nurseries across the country. An optional third phase could be to improve the prototype system and develop a commercial prototype that would have the additional capability of being able to set-down containers in a spaced configuration. This report summarizes development status of the project at the 8-month stage.

Trident Design Overview

When designing Trident, the ability to pick up and set down containers in an efficient manner, the ability to interface with a common prime mover, overall cost, and the amenability to the largest possible number of growers were the principal issues considered. The following design constraints were decided upon after careful consideration of data gathered from numerous field trips and surveys:

- Trident should be able to exceed the container handling rate of the most efficient multi-person team observed during field trips to nurseries around the country.
  - Trident will need to handle 32,000 1 gallon containers per 8 hour working day.
- Trident should pay for itself in one year.
  - The overall cost should be within the price range of typical add-on tooling systems (i.e. between $25K and $45K).
- Trident should be developed as an add-on tool that can interface easily with a tractor commonly used in nurseries.
- Trident should be able to load and unload containers from trailers typically used in the nurseries.
  - Trailers can vary in size from 4'x 8' to 8' x 16'.
- Trident should require no more than a single operator.
- The quality and reliability of container handling by Trident should be equivalent or better than that of manual methods.
- Trident should be able to handle all of the most extensively used types and sizes of containers.
  - Over 87% of the containers used in the industry are 1-5 gallon containers. Therefore, Trident should be able to handle container sizes ranging from 1-5 gallons.
- Trident should be able to pick up and drop off containers in both can-to-can and can-tight configurations.
  - The operator should be able to select the required configuration for setting down and picking up containers.
  - Spaced configurations will have to be accommodated in the final design. At this stage the focus is to be able to deal with can-to-can and can-tight configurations only.
- Trident should be able to operate on various types of ground-covering materials.
  - Trident should be able to accommodate all surface materials observed on field-trips excluding thin plastic (Poly) ground-coverings. (Gravel, compacted dirt, geo-textile and similar durable materials will be accommodated).
- Trident should be able to operate within the constraints of a majority of the existing over-wintering structures with little to no modification of these structures.
  - Trident should be able to accommodate over-wintering structures that can be accessed from the sides, or structures in which the prime mover can access the pots easily from the front of the structure.

Based on these design guidelines, and following the conclusions drawn from existing systems, the decision was made to develop the Trident system as a set of modular components. The basic premise of the design was that Trident would be a tool that could be attached to a locomotion platform. The locomotion platform could be any one of a variety of prime movers used in the nursery industry. Trident itself will be subdivided into five modular components; (1) the alignment articulation, (2) the gross advance system, (3) the tine storage, (4) the loading head, and (5) the container grabber. A schematic illustrating the location of each of these modules, with respect to the other modules, is shown below in Figure 6:

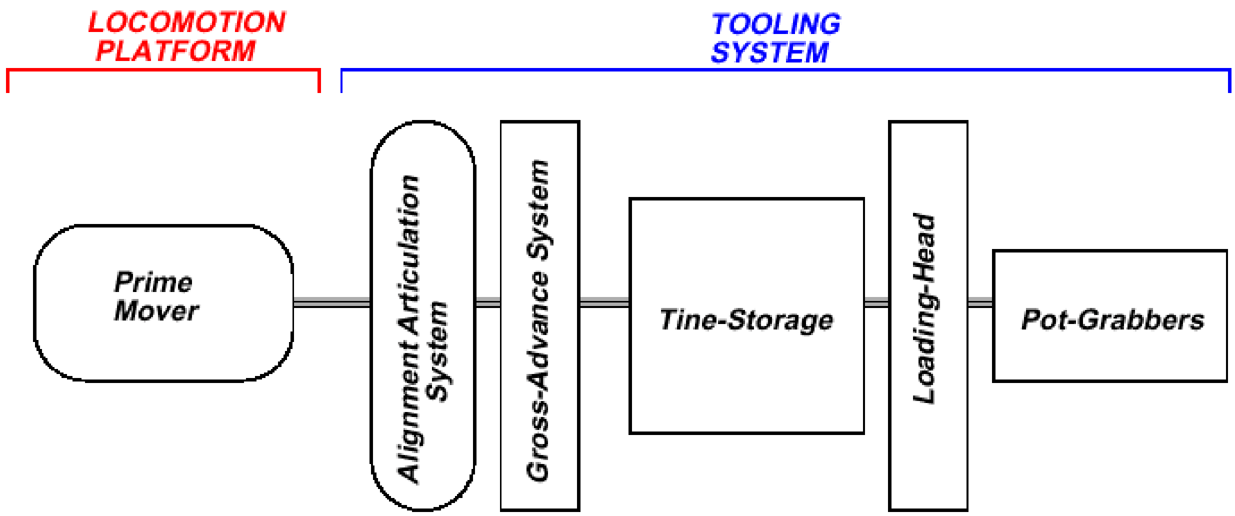


Figure 6: Block-diagram illustrating the basic components of the automated container handling system

Each of the modules interconnects with the other modules and functions in the following manner:

- The pot-grabbers form the electromechanical system designed to grasp and lock-in the containers during the transition phase from the field to the tine-storage system during pick-ups and from the tine-storage system to the field during set-downs. This module will be fully automated and not require any operator control.
- The loading-head is an electromechanical system with an on-board controller, required to hold the pot-grabbers in place, to allow alignment of the pot-grabbers with the next row of containers to be grasped via its sideways, backwards, and up/down articulation, and also to lift up the grasped row of containers to transfer them to the tine-storage system. This system will be fully automated and not require any operator control.
- The tine-storage system was designed to store a large number of containers that were grabbed off the field or off a trailer so that many containers can be loaded or unloaded from a trailer in one step, preventing the need for the grasping device to move back and forth between the trailer and the field each time it grabs a row of containers. This system will also need the capability to shift vertically (a vertical lift system akin to those on forklifts) so that the tines can be raised or lowered to the appropriate height to load or unload the trailers. This system will be partly automated, and rely partly on operator-control. The hand-off from the pot-grabbers to the tine-storage system will be automated while the shift between loading and unloading, and the vertical alignment with the trailer will be controlled by the operator.
- The purpose of the gross-advance system is to advance the tine-storage system and pot-grabbers into the rows of containers once the tooling system is correctly aligned with the containers. The rate at which the tines are advanced will be controlled by this system to allow the containers to be picked up one row at a time. This module will be automated.

- The alignment articulation system is needed to provide fine-alignment between the container loading/unloading system and the container beds. This sensor-aided system will improve on the gross alignment performed by the operator. The system will be capable of lateral and rotational alignment.
- The prime mover will be controlled entirely by the operator. Its principal responsibilities will be performing gross movement between the trailers and the growing fields or over-wintering structures, and rough alignment of the tooling system with the containers.

In the pre-prototype stage the different modules were constructed as shown below:

Experimentation with several different designs for the pot-grabbers showed the articulated butterfly pinch-grabber design (see Figure 7) to be the most suitable for the task of handling containers.

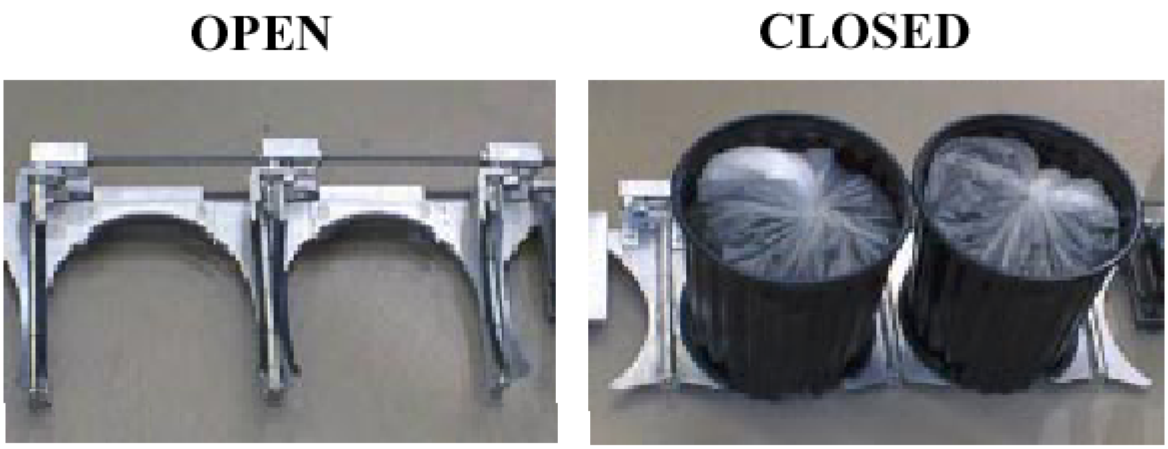


Figure 7: Articulated butterfly pinch-grabber system in the pre-prototype stage

The loading head module consists of a rectangular frame structure built from aluminum extrusions that holds the pot-grabbers and their articulation in a single setup, while also allowing for travel along the outside of the tines for lifting, backing up, and dropping off the containers onto the storage-tines.

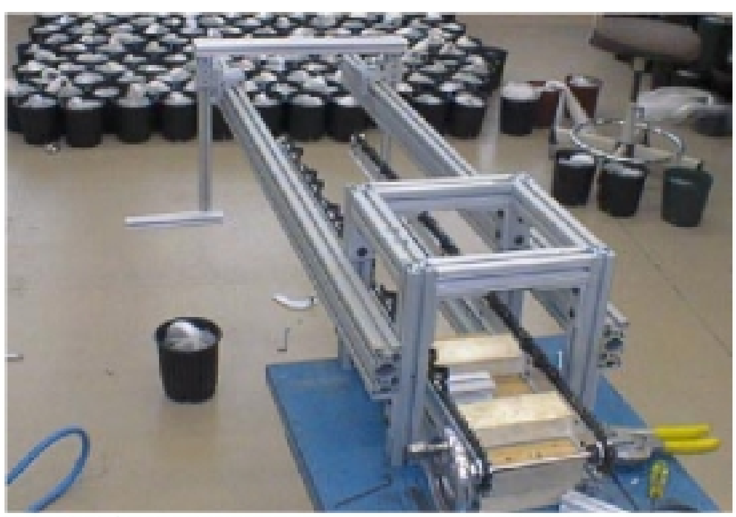


Figure 8: Loading-Head system in the pre-prototype, partial assembly stage

The tine-storage unit was designed with an integral conveyor chain-drive. The chain-drive could have a variety of different retaining features, such as brushes, rubber-lips, etc., attached to it.

Figure 9: Experimental conveyor-chain tine-storage system in the pre-prototype stage

The gross-advance system and the alignment articulation system were simulated manually for the prototype. The electromechanical aspects of the alignment articulation system were not completely specified because the type of articulation, degrees of freedom, and motion ranges are highly dependent on the final design of the tool, and also since this system could easily be implemented using a variety of existing actuation devices once the design of the tool is known. However, a possible sensing system for this module was investigated and a mockup of the sensor configuration was built (but not integrated with the prototype). Details of this sensing system are presented in the following sections. A John Deere tractor was used as the prime mover for the prototype.

Figure 10 below shows the completed assembly of the experimental prototype.

Figure 10: Completed assembly of experimental prototype

Figure 11 illustrates the different components of the final design of the Trident system as is currently envisioned:

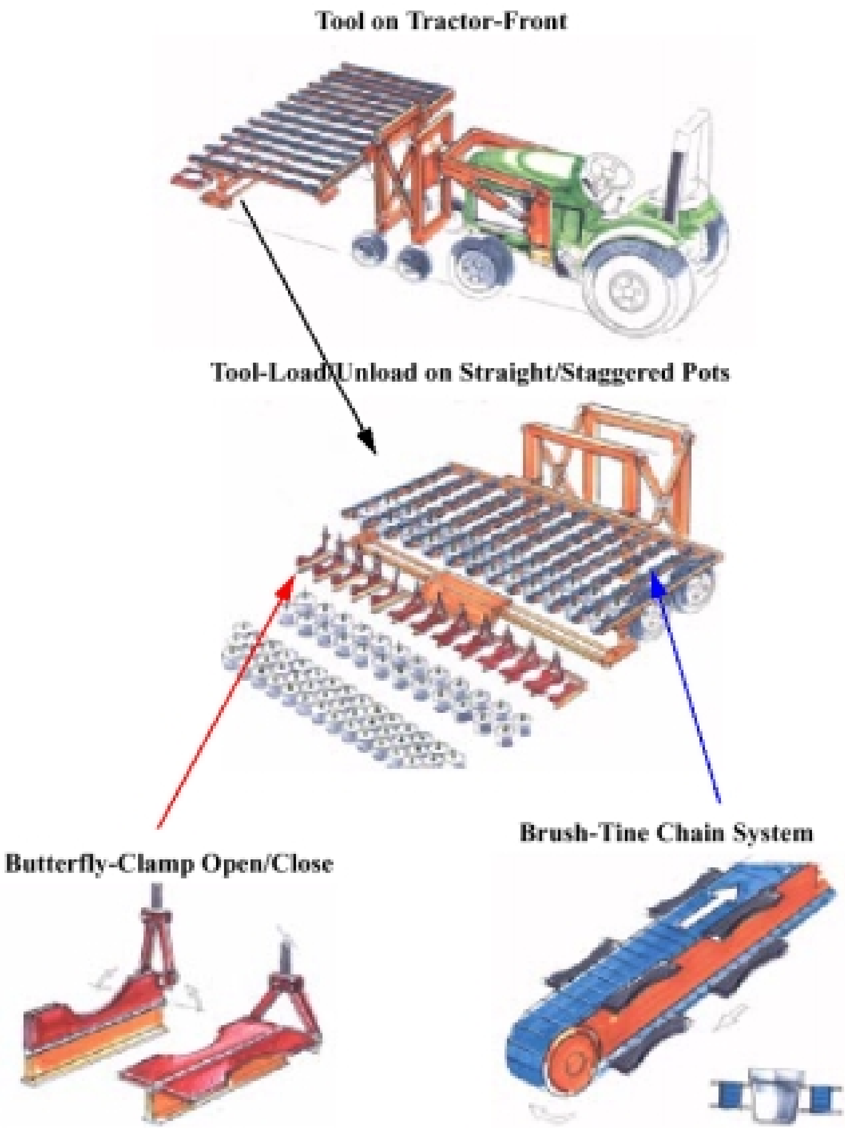


Figure 11: Final design concept for Trident system

Sensing System Requirements

A sensing system that satisfies all the alignment needs for the Trident system would have the following requirements:

Feature	Requirements	Comments
Alignment in x	Accuracy of 1or 2 inches	Should be able to indicate when tines of pot-grabbers are aligned with spaces between containers.
Alignment in y	Short range capability Accuracy of 1 - 2 inches	Should be able to tell how far off the first row of containers is from the loading-head.
Alignment in θ	~10 degree accuracy	Should be able to improve on operators alignment of loading-head, by detecting misalignments within the 5-30 degree range.
Speed	On the order of 100Hz	Should be capable of rapidly detecting misalignments.
Cost	Low cost (<$100)	Robustness can be enhanced through redundancy which will require many low cost sensors.
Availability of sensors	Easily available	The sensors should be easily available nationwide in order to facilitate repairs when necessary.
Robustness	Highly robust to rugged conditions	It is extremely important that the sensors be able to withstand rugged conditions in an outdoor environment.
Sensor sensitivity to environmental conditions	Minimal	Should be able to function accurately under different weather and lighting conditions outdoors.
Sensor sensitivity to reflecting surface color, reflectivity, etc.	Minimal	Should be able to detect the many varieties of containers currently being used in the nursery industry. (Different colors, sizes, shapes, etc.)
Physical dimensions of sensors	Small (<3 cubic inches) Light-weight	Should be able to fit on the tines of the pot-grabbers without impeding their actuation.
Ease of maintenance	Low cost	Should not require high-cost or complex maintenance.
Computation and power requirements	Minimal	Should be capable of microprocessor control with low power consumption.
Calibration requirements	Simple	Should not require a complicated calibration process.

Table 1: Requirements of Trident's sensing system

Summary of Sensor Search

Several different types of sensors were considered as possible candidates for Trident's sensing system. The advantages and disadvantages of each sensing technology were compared in relation to the sensing requirements of the system. Table 2 below illustrates the advantages and disadvantages of each of the categories considered:

Sensor Type	Advantages	Disadvantages
Radar	▪ High accuracy ▪ Can be custom designed	▪ High initial cost ▪ Must be custom designed
Laser Range Finders	▪ High accuracy ▪ Easily available	▪ High cost ▪ Bulky
Sonar	▪ Easily available ▪ Relatively small ▪ Simple setup ▪ Simple data analysis ▪ Not affected by lighting conditions	▪ Low data acquisition rate ▪ High cost for good accuracy
Optoelectronic -- Infrared (IR)	▪ Decent accuracy ▪ Small size ▪ Low cost ▪ Easily available ▪ Simple setup ▪ Simple data analysis	▪ Can be sensitive to lighting conditions
Vision	▪ High accuracy	▪ Complicated data analysis ▪ Highly sensitive to lighting conditions ▪ Can be bulky ▪ Relatively high cost
New Experimental Sensors (Ex: Sensor Skin developed by NASA)	▪ Could give high accuracy ▪ State-of-the-art technology	▪ Not easily available ▪ Could involve complex data analysis ▪ Can be relatively high-cost

Table 2: Comparison of different sensor-types consisdered for Trident's sensing system

Of all the sensing technologies considered, infrared sensors appeared to be the most suitable candidate for satisfying most of Trident's sensing system requirements. Therefore, several different types of infrared sensors were researched. Based on relative cost, accuracy, size, and availability the GP2D02 sensor by SHARP was clearly the most promising sensor we could find.

GP2D02 Sensor Specifications[2]

Of all the sensors surveyed, the GP2D02 sensor matched the most requirements of Trident's sensing system. Hence, the GP2D02 infra-red sensor, developed by SHARP, was the sensor of choice. Figure 12 below shows a top-view and side-view of these sensors.

[2] Information provided in this section was obtained from documentation provided by Acroname Inc. (a distributor of GP2D02), and SHARP Microelectronics of the Americas (manufacturers of GP2D02).

Some of the published features of this sensor that made it attractive were:

- Compact housing (see Figure 12)
- Low cost (~$21.00 per sensor)
- Distance measuring with built-in PSD[3], infrared LED, and signal processing circuit
- Low sensitivity to color and reflectance properties of reflective obstacle
- High accuracy distance measuring by sequential position detection
- 8-bit serial measured output with direct connection capability to microprocessor
- Low current consumption at stand-by mode
- Simple external circuitry requirements
- High data acquisition rate (~ 200 Hz)
- Operating range of 10cm – 80cm (for white paper with 90% reflectivity)
- Easily available
- Required supply voltage of 5V

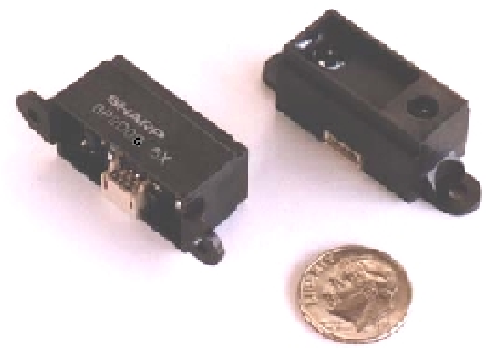


Figure 12: GP2D02 infra-red distance measuring sensors

Some published specifications for the GP2D02 sensor are tabulated below:

Parameters	**Rating**	**Units**
Operating Supply Voltage	4.4 to 7	V
Operating dissipation current when obstacle is 20cm away (Avg. Value when detecting input signal during operation)	Typ:22 Max: 35	mA mA
Off-state dissipation current when obstacle is 20cm away (Avg. Value when detecting input signal during operation)	Typ:3 Max:8	µA µA
Operating Temperature	-10 to 60	ºC
Storage Temperature	-40 to 70	ºC
Wavelength (infrared LED)	780 to 920	nm

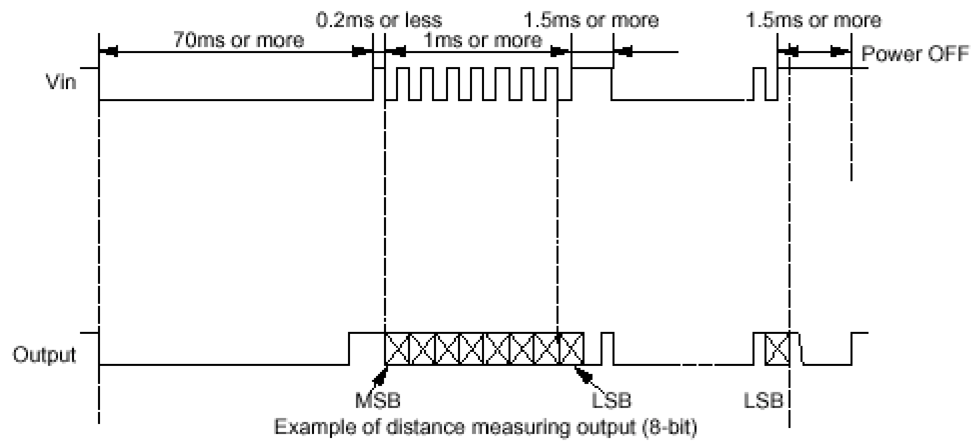
Table 3: Published specifications for the GP2D02 sensor

An explanation of the procedure to drive the GP2D02 via a microprocessor can be summarized as follows:

The serial interface between the sensor and the microprocessor is used to obtain measurements from the sensor. The sensor starts in an Off-state. (Very little current is consumed in this state since the open-drain input floats high). To initiate a measurement, the sensor is brought to a low On-state for 70ms or until the output voltage from the sensor goes high, allowing the sensor to take a measurement. The microprocessor must next provide the clock for the

[3] Position Sensing Device (PSD)

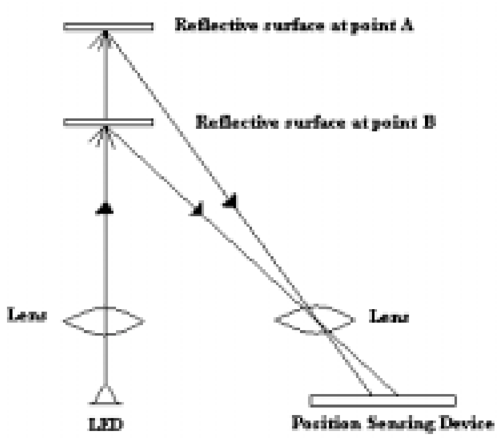
output of a serial byte from the sensor. This is done by alternating the input voltage line 9 times between high and low, at a frequency of up to 0.2ms for each state. A bit of the output byte from the sensor becomes available on the output voltage line after the first transition of the input voltage line from low to high, and at each said transition thereafter. Once the output byte is read, the input voltage must be kept high (floating) for 1.5ms or more to allow the sensor to reset for the next measurement. Note, the first bit sampled will be the most significant bit. The measurement time can be accelerated if the capability of detecting the initial rising edge of the sensor output during



measurement exists. Once this rising edge is detected, (indicating the measurement is complete), the microprocessor can begin clocking out the data byte.

Figure 13: Timing chart for GP2D02 sensor
(Presented from sensor documentation provided by SHARP)

The underlying principal of the GP2D02 sensor distance measuring system can be summarized as follows:



The position of the optical spot on the position sensing device (PSD) changes when the reflective object is moved (see Figure 14). Thus, by processing the position of the optical spot on the PSD, the distance to the reflective object (on a straight line in front of the emitter LED) can be determined.

Figure 14: Principal of triangulation (Reproduced from documentation provided by SHARP)

The GP2D02 sensors have previously been used in several different applications such as exercise equipment, forklifts and heavy duty equipment, automatic toilets, power controls and paper sensors in copy machines, etc. Thus, they have been proven to be robust sensors in a variety of industry applications.

Experimental Investigation of GP2D02 Performance

Several experiments were carried out to evaluate the performance of the GP2D02 sensor under different conditions that could be encountered in the nursery environment. A summary of these experiments follows:

- GP2D02 sensitivity to reflectivity of obstacle:

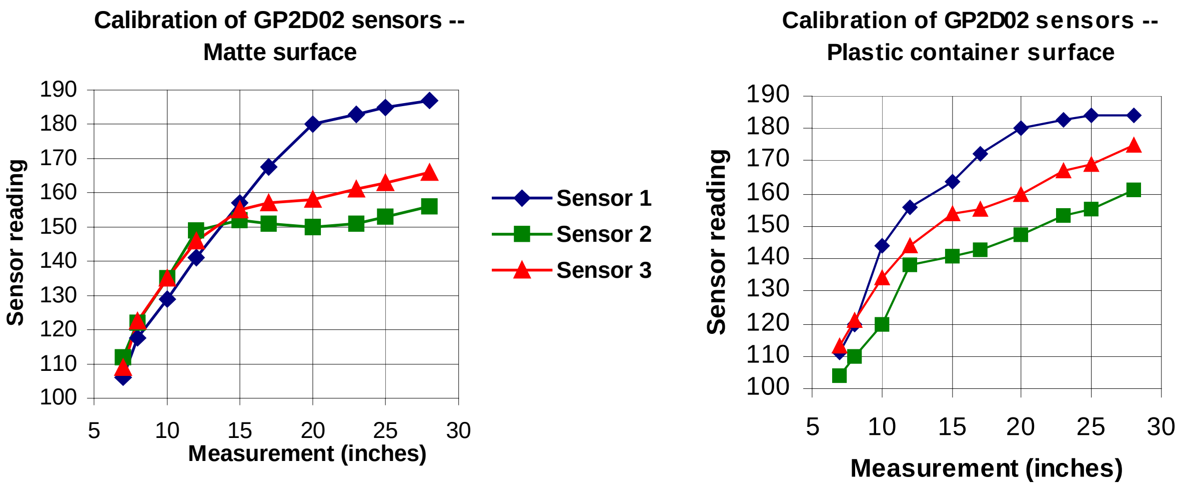


Figure 15: GP2D02 sensitivity to reflectivity of obstacle

The reflectivity of the obstacle surface does affect the sensor output. However, since a majority of the containers are made of materials with similar reflectance properties, the output of the GP2D02 sensor is not significantly different when compared across different types of containers.

- GP2D02 sensitivity to lighting conditions:

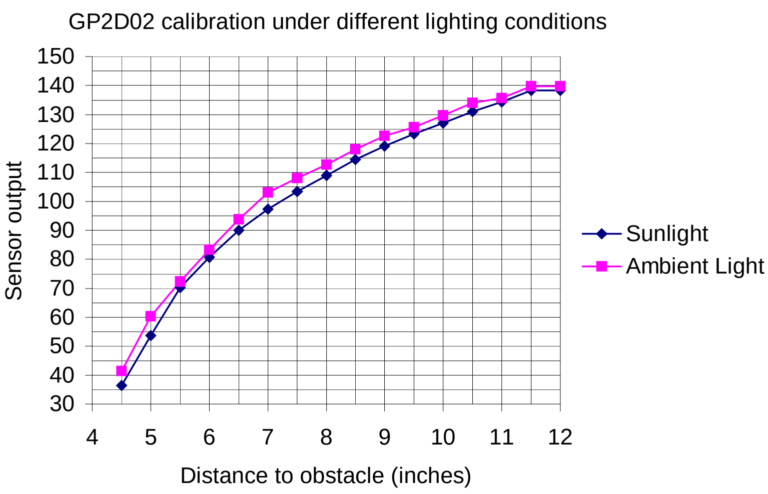


Figure 16: GP2D02 sensitivity to lighting conditions

The GP2D02 sensor performance was not significantly affected by lighting conditions. The only significant effect of light was that the maximum range of the sensors decreased to approximately 1.5 feet in bright sunlight. The angle at which the sunlight hits the sensor however, can affect the performance of the sensor significantly. Some experimentation was done to evaluate the affect of sunlight hitting the receiver in the sensor at different angles. These experiments indicated that the sensors could detect obstacles within a 10 inch range even when the sun was approximately 10 degrees above direct line of sight into the receiver. Since the containers shield the sensors from sun angles below this, the sensors should be able to direct the alignment of the pot-grabbers for all conceivable sun-angles in the container-field scenario.

- GP2D02 sensitivity to color and shape of reflecting surface:

  Containers of several different widely-used colors and shapes were used as obstacles, and the GP2D02 output was compared across the variety of containers. These experiments showed the GP2D02 sensitivity to color and shape of the containers is insignificant.

- GP2D02 sensitivity to protective shielding:

  Glass or clear plastic (acrylic) of 0.25inch thickness placed within 2mm of the sensor did not affect the performance of the GP2D02. The manufacturers advised placing any protective cover directly in front of the sensor (as close as possible to the transmitter) in order to eliminate interference with the transmitted IR beam.

- GP2D02 beam-shape and sensitivity to surrounding obstacles:

  According to information provided by the sensor distributor Acroname Inc., the GP2D02 IR beam is shaped as shown below (see Figure 17). Experimentation confirmed that the beam spreads out in 3 dimensions as indicated by Acroname Inc. However, the accuracy of the GP2D02 degraded significantly for obstacles beyond 1.5 feet from the sensor. Moreover, experimentation revealed the useful range of the GP2D02 to be 3.5 inches – 1.5 feet in ambient light. This maximum useful range was further decreased to approximately 10 inches in sunlight. Further experimentation proved that any obstacles (including the floor) beyond 2 inches above, below, or on the sides of the sensor did not interfere with the sensor performance.

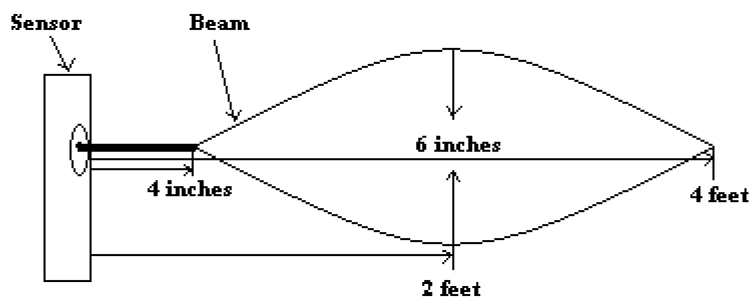


Figure 17: Beam shape of GP2D02

- GP2D02 calibration issues:

  Figure 15 indicates the need for calibrating the GP2D02 sensors individually. The sensor outputs varied significantly from sensor to sensor under identical environmental conditions. However, there was no indication that the sensor calibration changed with time (i.e. there has been no indication thus far, over a 4 month period, that the sensors need to be re-calibrated). The calibration of the sensors does change however, with lighting conditions (especially with the angle at which the sunlight hits the receiver). Thus, using these sensors for absolute distance measurements in the field could prove to be difficult.

- GP2D02 performance in a variety of possible field-container scenarios:

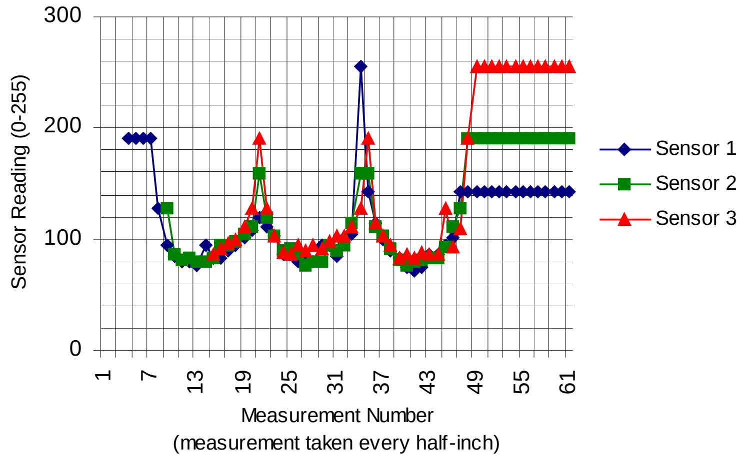


Figure 18:
Sensors: 3.5" apart, 3.5" above the floor, 6" away from pots.
Containers: can-to-can, indoors, green, non-smooth surface, on carpeted floor
Light: Ambient light
Note: Sensor data from three sensors have been superimposed for ease of evaluation

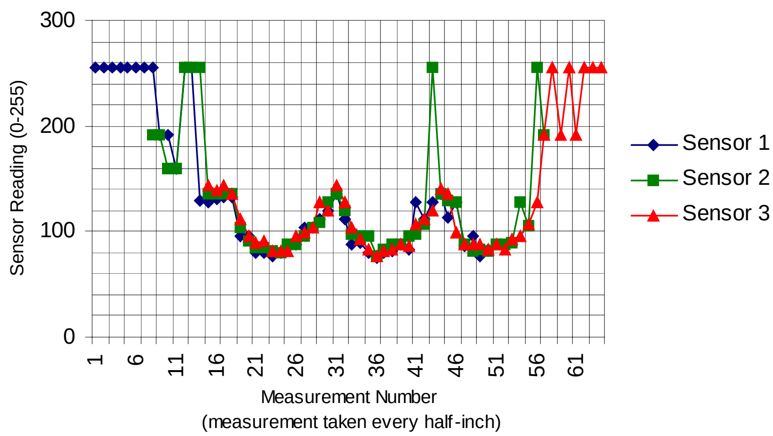


Figure 19:
Sensors: 3.5" apart, 3.5" above the floor, 6" away from pots.
Containers: can-tight, indoors, green, non-smooth surface, on carpeted floor
Light: Ambient light
Note: Sensor data from three sensors have been superimposed for ease of evaluation

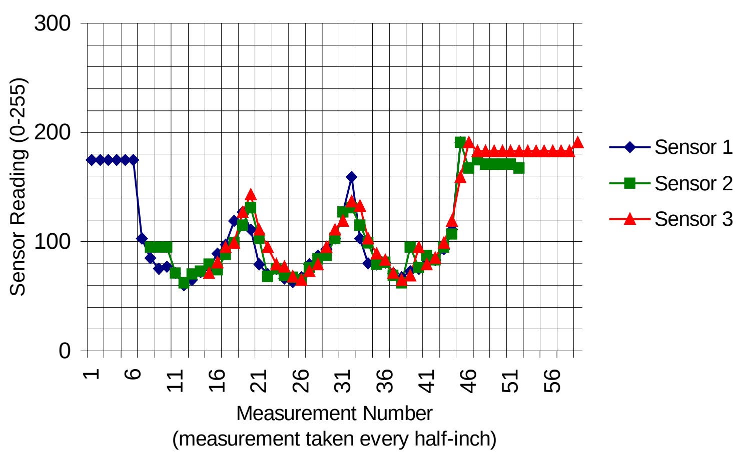


Figure 20:
Sensors: 3.5" apart, 3.5" above the floor, 6" away from pots.
Containers: can-tight, indoors, green, non-smooth surface, on semi-specular surface
Light: Ambient light
Note: Sensor data from three sensors have been superimposed for ease of evaluation

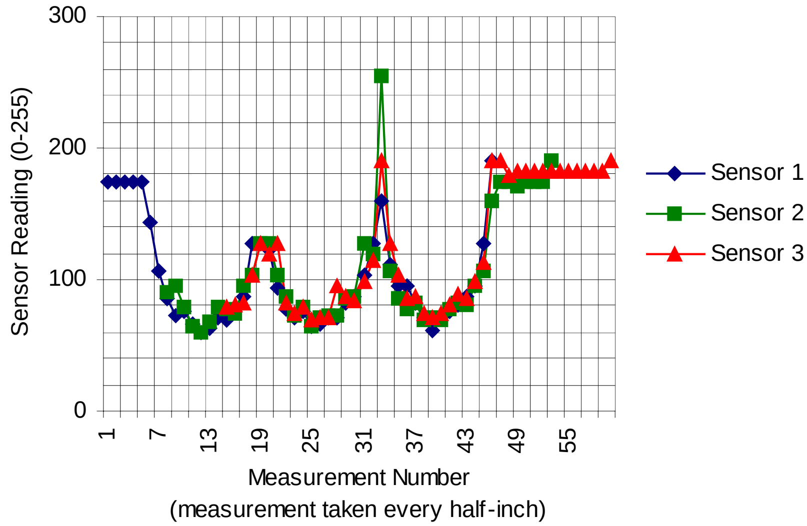


Figure 21:
Sensors: 3.5" apart, 3.5" above the floor, 6" away from pots.
Containers: can-to-can, indoors, green, non-smooth surface, on semi-specular surface
Light: Ambient light
Note: Sensor data from three sensors have been superimposed for ease of evaluation

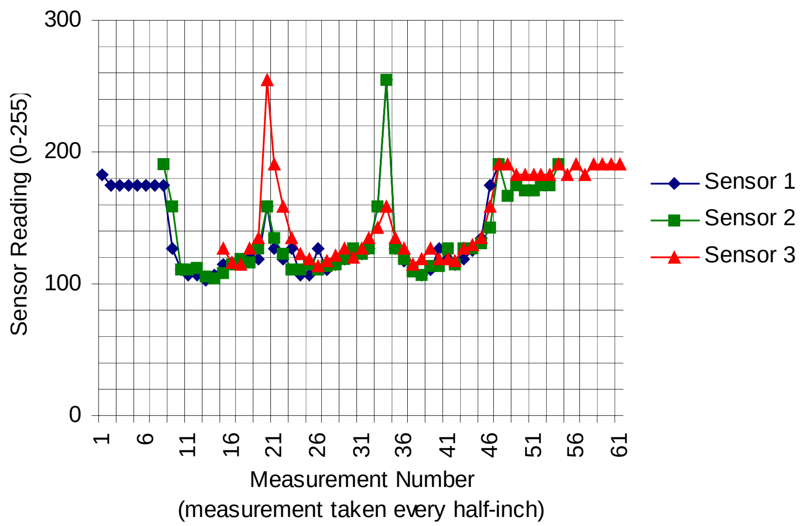


Figure 22:
Sensors: 3.5" apart, 3.5" above the floor, 9" away from pots.
Containers: can-to-can, indoors, green, non-smooth surface, on semi-specular surface
Light: Ambient light
Note: Sensor data from three sensors have been superimposed for ease of evaluation

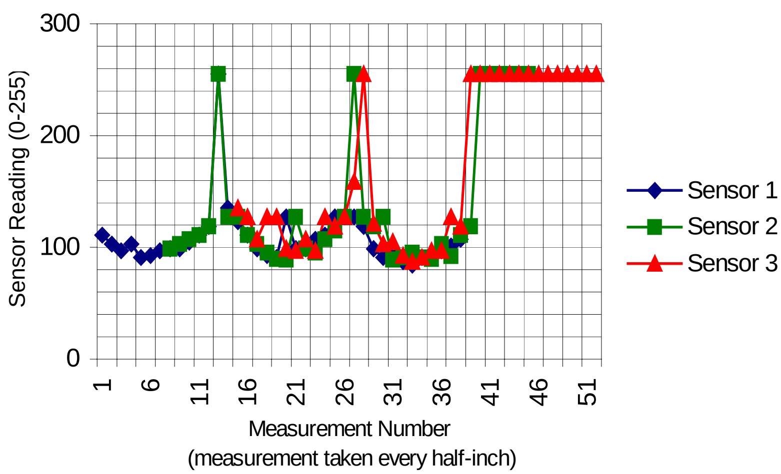


Figure 23:
Sensors: 3.5" apart, 3.5" above the floor, 6" away from pots.
Containers: can-to-can, outdoors, green, non-smooth surface, on stone-paved surface
Light: Varying sunlight conditions (Cloudy day)
Note: Sensor data from three sensors have been superimposed for ease of evaluation

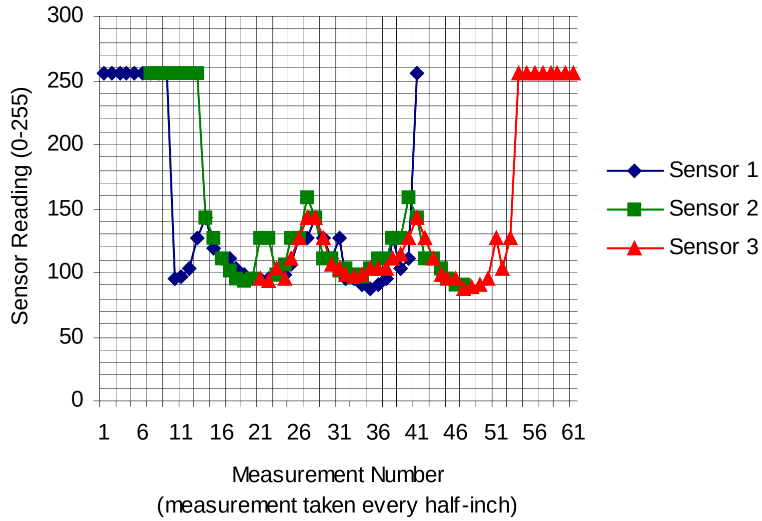


Figure 24:
Sensors: 3.5" apart, 3.5" above the floor, 6" away from pots.
Containers: can-to-can, outdoors, green, non-smooth surface, on stone-paved surface
Light: Bright sunlight conditions
Note: Sensor data from three sensors have been superimposed for ease of evaluation

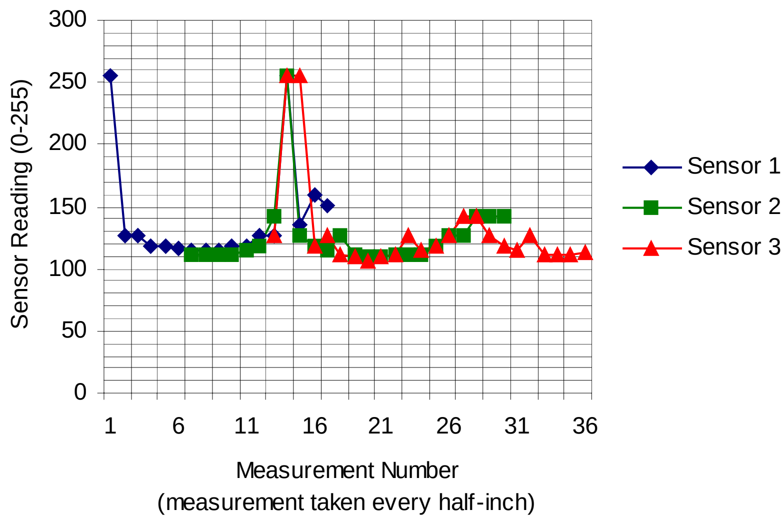


Figure 25:
Sensors: 3.5" apart, 3.5" above the floor, 6" away from pots.
Containers: can-tight, outdoors, green, non-smooth surface, on stone-paved surface
Light: Bright sunlight conditions
Note: Sensor data from three sensors have been superimposed for ease of evaluation

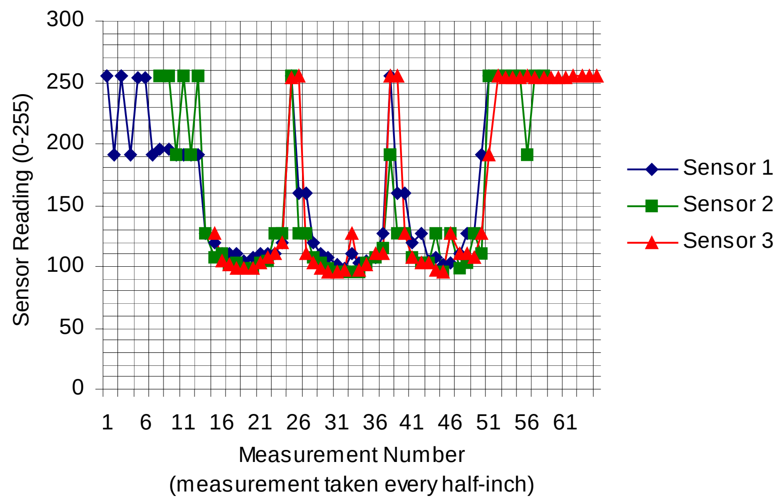


Figure 26:
Sensors: 3.5" apart, 2.5" above the floor, 7" away from pots.
Containers: can-to-can, outdoors, green, non-smooth surface, on stone-paved surface
Light: Bright sunlight conditions
Note: Sensor data from three sensors have been superimposed for ease of evaluation

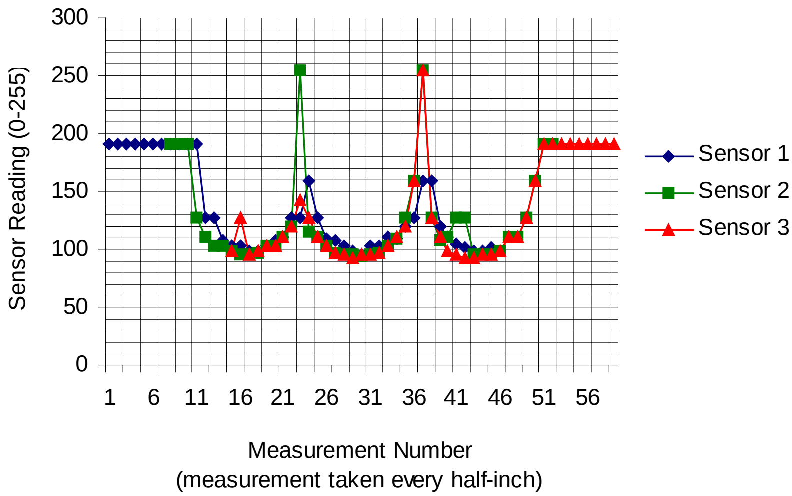


Figure 27:
Sensors: 3.5" apart, 2.5" above the floor, 7" away from pots.
Containers: can-to-can, outdoors, green, non-smooth surface, on stone-paved surface
Light: Bright sunlight conditions (Sun setting to the left of the pots)
Note: Sensor data from three sensors have been superimposed for ease of evaluation

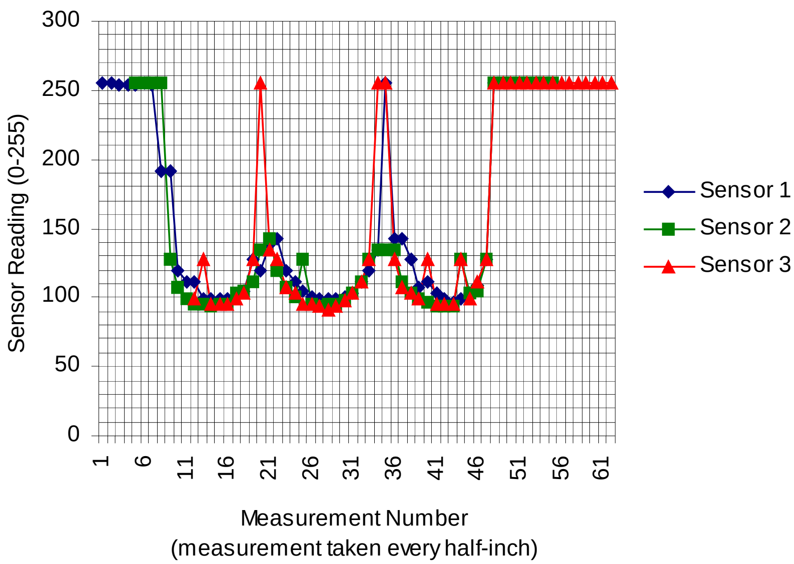


Figure 28:
Sensors: 3.5" apart, 2.5" above the floor, 7" away from pots.
Containers: can-tight, outdoors, green, non-smooth surface, on stone-paved surface
Light: Bright sunlight conditions (Sun setting behind the pots)
Note: Sensor data from three sensors have been superimposed for ease of evaluation

The overall performance of the GP2D02 sensors was promising and hence, a prototype of a possible sensing system was built using these sensors. Details of this sensing system prototype follows in the next section. Additional experimentation remains to be done to investigate the sensor performance in dusty environments, in rainy conditions, in snowing conditions, with muddy containers, etc. However, the performance of the GP2D02 sensors in the experiments carried out thus far was sufficiently promising to build an experimental prototype of a possible sensor configuration for Trident.

Experimental Prototype of Sensing System

An experimental prototype of a possible sensor configuration for Trident's sensing system was built using GP2D02 sensors. The basic structure of the prototype consisted of a sliding head (built using aluminum extrusions) with 4 tines spaced so that they could fit around three containers (see Figure 29)[4]. GP2D02 sensors were placed on

[4] The experimental prototype structure was constructed by Jan Falkowski.

each of the tines and also in between each pair of tines. Thus, the prototype consisted of 7 GP2D02 sensors. Simple circuitry was built to control the sensors via the parallel port of a laptop running Windows 95[5]. Although the sensors will be controlled via a microprocessor on the final prototype, a laptop was used in the experimental prototype to allow more convenient software programming and debugging. A 9V battery supplied power for the sensing system. All software coding was done in C++.

Figure 29: Experimental prototype of possible sensor-configuration for Trident sensing system

Initially, a simple program was written to allow acquisition of data from the sensors.[6] Once data acquisition was reliably established, the sensors were individually calibrated, and look-up tables were constructed for each sensor. Within the 3.5 inch to 9 inch range, each sensor output was recorded at every quarter-inch in the look-up table. The look-up tables then provided a means to convert the sensor readings (0-255) to distance measurements simply using linear piece-wise interpolation. (The look-up table used for the sensors in the prototype is shown below to illustrate the need for calibrating each sensor individually.)

[5] Christopher P. Urmson was principally responsible for building the sensor circuitry and writing the initial data acquisition code.

[6] The observed sensor response to distance from the reflecting surface was different from that published. According to published data, the sensor readings should decrease in magnitude with greater distance to the obstacle (~1/x relationship). The observed response was an increase in the magnitude of the sensor reading with increased distance to the obstacle. This difference was attributed to some fault in the data acquisition code. However, since the sensors responded in a consistent manner to the distance to the obstacle, since the experimentation was calibration-based, and since the prototype was built for the purpose showing proof of concept, investigating this difference was postponed until the control of the sensing system was moved to a microprocessor.

Distance (inches)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
3.50	17	16	19	17	17	23	14
3.75	19	25	28	20	20	33	18
4.00	21	35	37	23	24	43	23
4.25	28	45	47	28	34	53	32
4.50	35	55	57	33	45	63	41
4.75	43	64	68	42	53	72	50
5.00	51	73	79	51	61	82	59
5.25	58	79	84	57	69	89	65
5.50	65	86	89	64	76	96	72
5.75	70	91	95	70	82	102	77
6.00	75	97	101	76	87	109	83
6.25	81	102	105	81	92	114	89
6.50	87	107	111	86	96	119	95
6.75	90	111	115	90	100	123	98
7.00	94	115	118	94	104	127	101
7.25	97	118	122	98	108	131	106
7.50	101	121	125	101	111	134	111
7.75	104	125	128	104	114	137	113
8.00	107	128	131	107	117	139	115
8.25	109	131	134	110	120	142	117
8.50	112	133	136	112	122	145	119
8.75	115	135	139	115	125	147	122
9.00	117	137	141	117	128	149	124

Table 4: Look-up table used for sensor-reading to distance conversion for the GP2D02 sensors used in experimental prototype of Trident sensing system. (Note: Calibration of the sensors was done in ambient light since preliminary experiments were carried out indoors).

The underlying principal of the adopted sensor configuration was to minimize error through redundancy. Since the GP2D02 sensors are not highly accurate sensors, much noise is observed in the sensor output. However, by averaging the readings of many sensors (while disregarding extreme outliers), errors can be minimized, and a robust sensing system can be created. The sensors were configured in a manner which allows alignment of the loading-head in X, Y, and θ in the following manner[7]:

[7] The authors designed the sensor configuration and alignment strategies in collaboration with Dr. Anthony Stentz and with input from the other Trident team members.

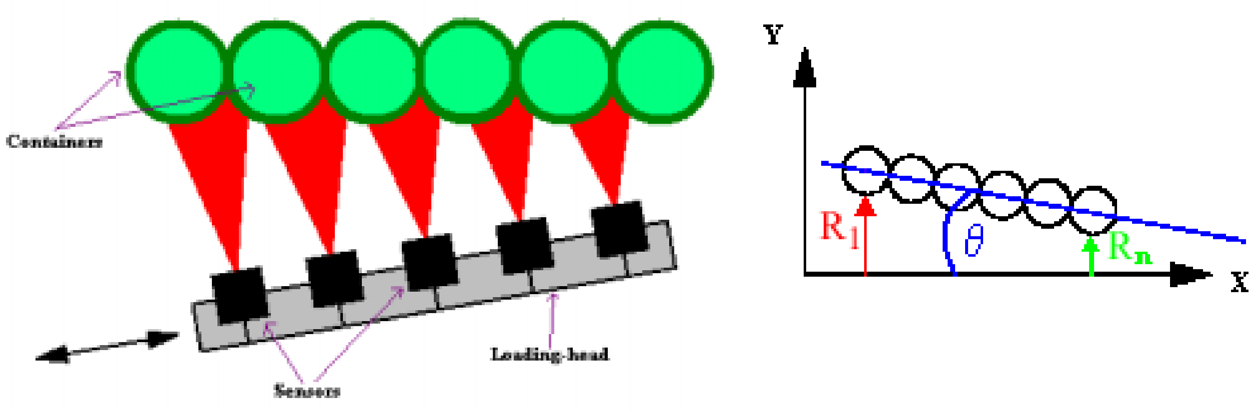


Figure 30: X, Y, and θ alignment of the loading-head

- Alignment in X:

  Alignment in the X-direction (lateral alignment) can be achieved by comparing the tine-sensor outputs and the inset-sensor outputs. If the tine sensors all indicate much larger distances than the inset sensors (the sensors in between the tines), the loading-head is aligned in the X-direction with the containers. If not, the sensors on the two end-tines can be checked to determine in which direction the loading-head should be shifted. If $R_1 >> R_n$ (see Figure 30), the loading-head should be shifted in the direction of R_n, and vice versa. The distance by which the loading-head should be shifted in order to align it with the containers can also be estimated. A comparison of the difference between the tine-sensor readings (excluding the two end-tine sensors) and the inset-sensor readings, to the radius of the containers, will provide an estimate of how far the loading-head needs to be shifted for alignment. Note, when making any comparisons between sensor readings, it is vital to first convert the reading to the corresponding distance measurement via the calibration table.

- Alignment in Y:

  Alignment in the Y direction is the simplest of the three since it only requires knowing the length of the tines in the pot-grabbers, and indicating when the tines are sufficiently advanced (between the containers) in order to firmly grab the row of containers. Hence, the tine-sensors will provide information about whether the tines are about to hit anything, and the inset-sensors will provide information about how far the tines are advanced between the containers. The redundancy of the sensor configuration will be significant in minimizing errors due to noise and sensor inaccuracies in the Y-direction alignment. By averaging several readings per sensor while disregarding extreme outliers, errors due to noise can be minimized for each individual sensor. By similarly averaging sensor readings over the entire array of inset-sensors, the average distance to the row of containers can be estimated. Individual sensor readings (averaged over several measurements of the same distance) are also important in order to detect non-uniformities in the container configuration.

- Alignment in θ:

  Alignment in θ can be achieved by comparing the differences in the distances measured by each of the sensors (taking into account whether each sensor is a tine-sensor or an inset-sensor) in relation to the horizontal separation of each pair of sensors considered. For example, θ can be calculated as the arctangent of the quotient, [(R_1-R_n) / horizontal separation of sensor_1 and sensor_n], where R_1 and R_n are as illustrated in Figure 30. This calculation can be repeated for all sensor pairs (sensor_1 and sensor_2, sensor_1 and sensor_3, sensor_2 and sensor_n, etc.), and the average calculated (disregarding extreme outliers) in order to estimate θ with minimum error. Furthermore, the direction in which the loading-head needs to rotate (clockwise or counter-clockwise) in order to be parallel with the row of pots can be determined by comparing the readings from sensors on each half of the loading-head. Rotation should occur such that the half of the loading-head that is farther away from the containers (larger R's) moves closer to the row of containers.

Simple algorithms for alignment of the loading-head with the containers, in X, Y and θ, were implemented in the experimental prototype of the sensing system. An analysis of its performance is described next.

Evaluation of Sensing System Prototype Performance

Two graphical demonstrations of the sensing capabilities were presented at the annual ANLA/HRI convention in Philadelphia on July 24th, 1999. The first demonstration illustrated the capability of the sensors to aid with lateral (X-direction) alignment. In this demonstration, the sensor mock-up (see Figure 29) was placed in front of three containers. When the loading-head was shifted from side to side a graphical display indicated whether the loading-head was aligned with the containers or not. If a misalignment occurred, the display indicated in which direction the head should be shifted for alignment to occur. Three figures were displayed on the screen illustrating move to the left, stop, and move to the right. The figure illustrating the appropriate action was highlighted in white. The graphical display[8] from this demonstration is shown below:

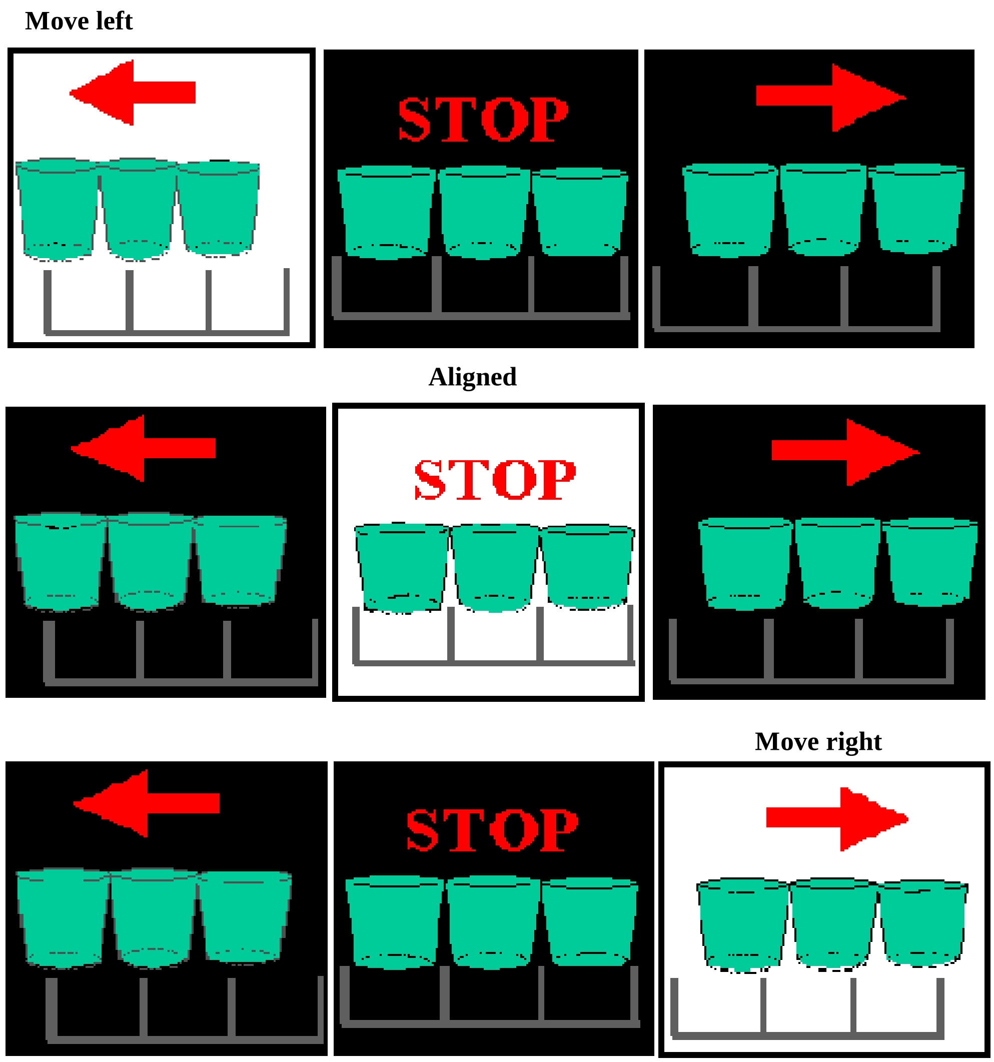


Figure 31: The 3 stages of the graphical display for demonstrating sensor capability to aid with lateral alignment

[8] Christopher P. Urmson assisted the authors in creating this graphical display.

The second demonstration displayed the profiling capability (used for alignment in Y) of the GP2D02 sensors. In this demonstration, a viewer was able to scan a single GP2D02 sensor in front of a container configuration and observe a real-time plot of the sensor output via a graphical interface[9].

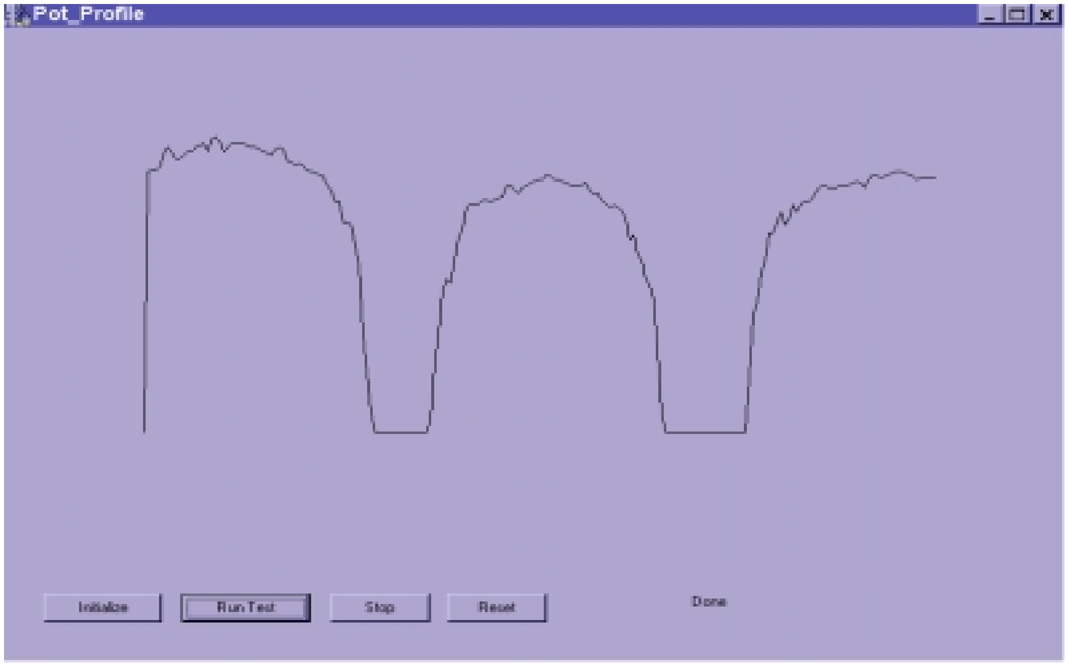


Figure 32: Graphical display for demonstration illustrating profiling capability of GP2D02 sensors

Both demonstrations were highly successful and well-received by the reviewers from the ANLA/HRI. Since the convention in Philadelphia, the sensor-configuration prototype has been further improved with the addition of angular alignment capability. With this capability, a viewer is able to align the loading-head at an angle (<= 35 degrees) and receive instructions for how to correct for the misalignment via a graphical interface (see Figure 33 below).

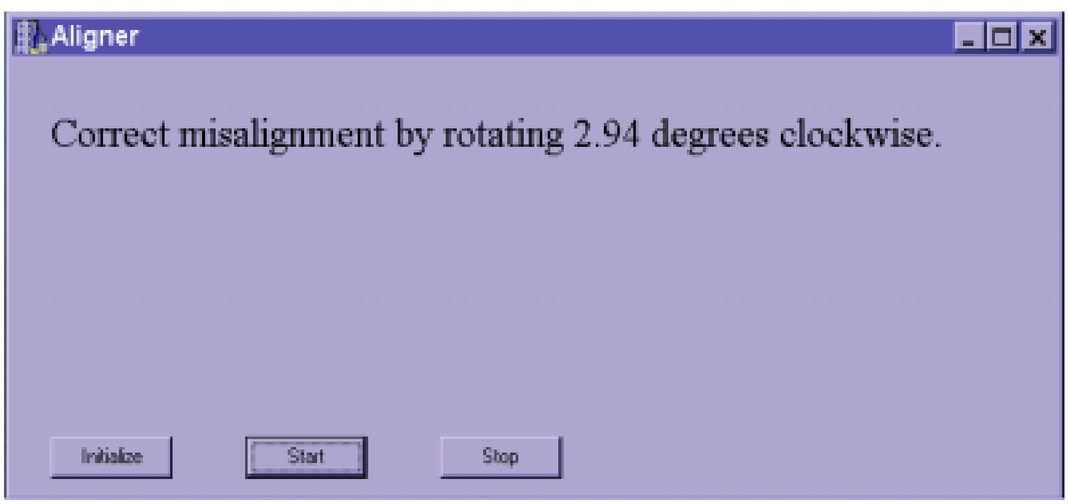


Figure 33: Display for illustrating angular alignment capability of sensor configuration

[9] Christopher P. Urmson assisted the authors in implementing this graphical interface.

The sensing-system performance in each of its alignment capabilities is reviewed below:

- Alignment in X :
  The sensing-system can detect lateral misalignments (in X-direction) with very high accuracy (within an error margin of 0.5cm). The system is also able to estimate the required shift (magnitude and direction) for alignment within the bounds of required accuracy ($\pm$ 1 inch) as long as the containers are within the active range of the sensors (3.5 to 9 inches).
- Alignment in Y:
  The sensing system's estimations of the distance to the containers in the Y direction are sufficiently accurate if the containers are within the active range of the sensors (3.5 to 9 inches), and if the lighting conditions during measurement and calibration are similar. The accuracy of the sensor performance under environmental conditions drastically different from conditions during calibration remains to be investigated.
- Alignment in θ:
  The sensing system's capability in angular alignment is highly dependent on its Y-distance measurement accuracy. Thus, due to the propagation of errors, the accuracy of the angle measurement is limited to $\pm$ 3 degrees. Furthermore, due to the limited active range of the sensors, the sensing-system capability in measuring angular displacement is further restricted to a maximum displacement of ~15 degrees from the row of containers. (Note that this range can be increased by discarding information of the sensors on the end-tines, and averaging over the other sensors). The system is accurately able to indicate in which direction the loading-head should be rotated for alignment.

The reported performance is based on the initial implementation of simplistic algorithms for alignment and distance/angle measurement. No averaging was performed over sensors. It is reasonable to expect significant improvement in system performance once averaging over all sensors (while discarding extreme outliers) is incorporated into the measurement algorithms. Thus, based on these initial results, the sensing-system performance was highly promising within the active range of the sensors in environmental conditions similar to conditions during calibration.

Discussion and Future Work

The main difficulties with the GP2D02 sensors were their limited active range (especially in sunlight), their need for individual sensor calibration, and their discrete-step measurements (probably caused by low quality analog-to-digital converters). The recently released successor to the GP2D02, the GP2D12, promises analog output, reduced sensitivity to reflectance properties of the reflecting surface, and lower cost (~$7.00 per sensor), in addition to the high quality performance of its predecessor. One of the most attractive features of the GP2D12 is its analog output. If all of the sensor outputs could be digitized via a single digitizer, it is possible that the sensor outputs will vary less from sensor to sensor, thus avoiding the need for individual sensor-calibration. Furthermore, using a higher quality analog-to-digital converter could reduce the discretization of the sensor output and provide more accurate measurements of misalignments.

As indicated in the previous section, averaging over all sensor data within a reasonable error margin can significantly improve system performance. Altering the sensor data-acquisition code to match the sensor output to that published by SHARP could also plausibly increase the range within which the sensors provide accurate data. Finally, field-testing of the sensing system needs to be carried out to evaluate its performance under different environmental conditions. Although initial experimentation indicates promising sensor performance in different lighting conditions, the performance of the entire system under these conditions needs to be evaluated. Moreover, the possible degradation of sensor calibration over time must be evaluated to allow for proper maintenance of the system. A safety element that identifies malfunctioning sensors could be a further useful addition to the system. [10]

[10] Since malfunctioning sensors tend to return 0 for all input conditions, this should not be difficult to implement.

At a higher level, the key components remaining to be accomplished are consolidating the different alignment procedures, transferring control of the sensing system to a microprocessor, integrating the sensing-system with the mechanical prototype of Trident, and introducing the operator into the loop. When consolidating the alignment procedures, the order of preference would be angular (θ) alignment first, lateral (X) alignment next, and finally, depth (Y) alignment. The extent of operator assistance in aligning the loading-head with the row of containers has not yet been finalized. As different details of the mechanical design get altered and finalized, the sensing system will have to be altered accordingly. Currently, it is envisioned that Trident will be able to pick up an entire row of containers at a time, and store several rows of containers in its storage tines before returning to the trailer to unload. (See Figure 34).

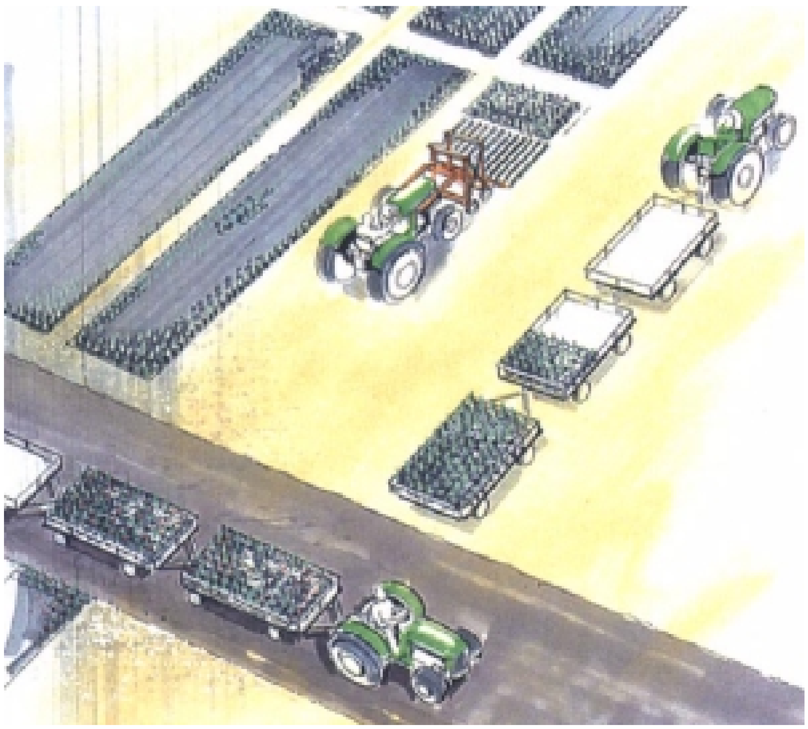


Figure 34: Conceptual schematic of Trident system operating in a nursery field, loading containers into trailers

The operator will be driving the prime-mover and providing gross-alignment to the Trident system. The operator will also be responsible for dealing with situations that Trident reports it is unable to handle (for example, if pots are overturned, or an obstacle is in the way, etc). A second laborer will drive empty trailer trains to the loading site and drive away the filled trailers as depicted in Figure 34. When dealing with over-wintering structures, it will be assumed that the Trident system will be able to gain access to the containers from the front or from the side of the cold-frames (see Figure 35):

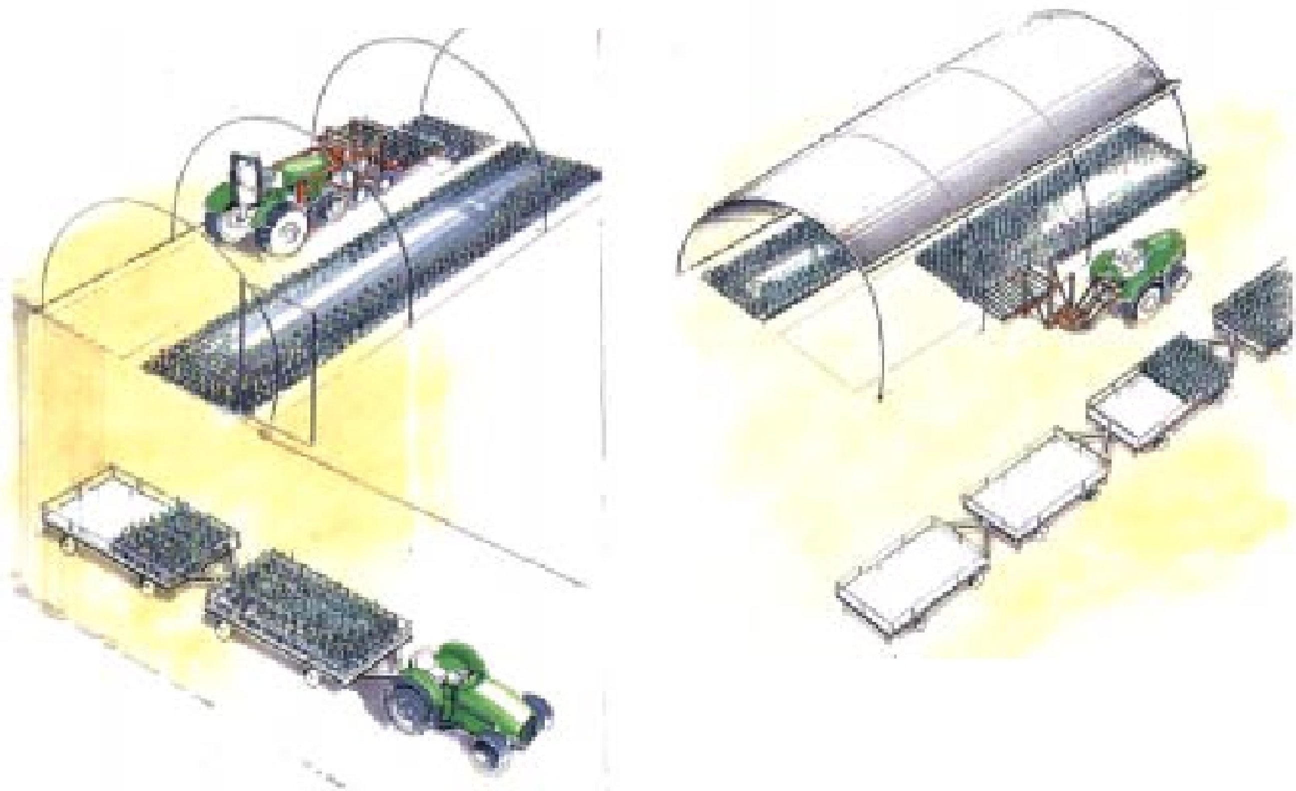


Figure 35: Conceptual schematic of Trident system operating in over-wintering structures

Once the entire Trident system is assembled and integrated with the sensing system, field-tests can be carried out to examine the plausibility of performing loading and unloading operations in a nursery using the current design. Alterations to the design can be made as needed. If averaging over many sensor readings does not produce sufficient accuracy for in-field operations, more complex methods such as model fitting, or Kalman filters can be incorporated into the sensor data analysis to improve accuracy. Having adopted a more complex analysis, if the inaccuracies are still too large, more expensive, high-accuracy sensors will have to be used, although this is an unlikely scenario.

Conclusion

The Trident system was designed as an intelligent grasping device to automate container-handling in the nursery industry. In order to align the grasping device with the containers, a robust sensing system is of paramount importance. A comparison of Trident's sensing requirements with the characteristics of different available sensing technologies pointed to optoelectronic infrared sensors as the most suitable sensing technology for the Trident system. A survey of available infrared sensors within the specified requirements for this system revealed the GP2D02 as the most promising candidate. Initial experimentation showed the GP2D02 sensor to be sufficiently satisfactory to warrant construction of a sensing system mockup using these sensors. An evaluation of the sensing system performance in aligning the grasping device with the containers (in X, Y, and θ directions) showed promising results. The main limitations of the GP2D02 sensors were their relatively small active range, their need for individual sensor calibration, and their discrete-step measurements. The recently released successor to the GP2D02 sensor, the GP2D12 sensor, promises to overcome some of the difficulties of its predecessor, and offers more attractive features. This report concludes that a viable, robust sensing system which satisfies Trident's alignment requirements can be built as outlined in this report, with the possible substitution of GP2D12 sensors for the current GP2D02 sensors, if field tests support the performance of the sensing system thus far.

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