Design of an autonomous robotic vehicle and development of a suitable gripper for harvesting sensitive agricultural products

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Abstract. This paper presents the design of an autonomous vehicle with a 5-link robotic arm and the design, prototype construction and initial testing of a robotic gripper for harvesting sensitive agricultural products. It is a modular design utilizing interchangeable "fingers", which allows the harvesting of different kinds (or sizes) of fruit. Static testing of the prototype gripper provided excellent results. The automated-robotic harvesting of crops is of high significance to the Greek economy.

Keywords: Autonomous harvesting vehicle, gripper, greenhouse automation.

1 Introduction

Nowadays, the technology of mechanical harvesting is focused on harvesting plants of large crops (e.g. wheat, corn) using special mowers of large size and cost. On the other hand, in spite of the great technological advances, the harvesting of vegetables and fruits depends primarily on human labor. This affects mainly the cost of production, the product's quality, as well as the safety of workers in crops that have been sprayed with pesticides (e.g. greenhouses). The main reasons for the shortage of automated solutions are:

1) The difficulty in tracking the fruits and
2) The difficulty in simultaneously cutting and collecting the fruits without damaging them.

These difficulties arise from the irregular shape of plants, the random position and orientation of the fruit, the possibility of partial or total coverage of the fruit by the plant's foliage, color similarity between the fruit and the foliage, and the vulnerability of many fruits to mechanical pressure or friction.

In general, the greenhouse crops are a growing part of agricultural production both in Greece and internationally. Moreover, these crops are of great economic significance because of the ability for off-season production. Inside greenhouses the creation of

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ideal conditions for plant growth is feasible by using climate control systems. These conditions are characterized by high humidity and temperature and increased levels of carbon dioxide (for increased photosynthesis). In addition, there is extensive use of fertilizers. These conditions favor the development of fungals and other phytopathogenic micro organisms harmful to plant growth. Therefore, frequent spraying with pesticides is necessary, along with the use of fertilizers.

During the harvest, it is generally difficult for farmers to travel long distances between crops to collect the fruits of the day. Usually, poor conditions are prevailing in the workplace, such as mentioned above. The use of automation in works such as watering, fertilizing, sowing, and in recent years in spraying and harvesting, is becoming increasingly necessary in order to increase productivity and reduce overall production cost. Moreover, in order to protect the agricultural force from pesticide use and tend to an increased demand for green products, it is often necessary to use fully or partially autonomous robotic systems.

As a result of the above, major research efforts have been made to apply advanced techniques in agriculture. Nevertheless, the use of human labor is still high, even in western countries where the hourly labor cost is very high, while automation is not applied to the same extent as it is in industry. Although the work of harvesting and spraying is primarily manual labor, the salaries are increasing. Therefore we need more applied research to allow for better allocation of human resources.

A brief summary of various research efforts so far is presented, so as to illustrate the intense research interest but also the lack of solutions for harvesting different fruit using the same harvester.

The research focuses on problems relating to driving, harvesting, spraying, seeding, etc. Tillet (1999) and Accacia et al. (2003) give an overview of robotic applications in horticulture. Various efforts for the automatic collection of fruits using a robot have been published. Specifically, the automatic harvesting of cucumber is discussed in Van Henten et al. (2004), of mushrooms in Reed et al. (2001), of lettuce in Cho et al. (2002), of strawberries in Kondo et al. (1999), of oranges in Plebbe et al. (2001), of sweet peppers in Kitamura et al. (2005) and of grapes in Monta et al. (1995). All of the above involve robots designed for a specific crop each. Only few publications are reported dealing with robots capable of working with more than one type of crop, such as those of Belforte (2006) and Kavousanos (2007). Details for the manufacturing of vehicles can be found in Astrand et al. (2002) where an autonomous robotic vehicle for weed control is presented, in Bak et al. (2004) which deals with an autonomous vehicle for finding weeds, in Southall et al. (2002) and Burgos et al. (2011) where autonomous vehicles are presented utilizing specialized computer vision systems for discriminating between crop and weed, and, in Billingsley (2000) where a driven tractor with machine vision is used.

This paper focuses on the automated, robotic harvesting of crops of high significance to the Greek economy. It involves the design of an autonomous vehicle equipped with a 5-link robotic arm and gripper. It presents the design, prototype construction and static testing of a robotic end-effector gripper for use in the collection of sensitive agricultural products. The gripper is comprised of the capturing mechanism, the driving motor and the motor electronics. It has a modular design which allows for adaptation to harvesting more than one kind (or size) of fruit at a time by utilizing interchangeable sets of “fingers”. Each set of fingers is of different shape, size and fruit-contact material.

The basic design of the vehicle, the robotic arm and the autonomous operation electronics, since they relate to the handling of the fruit, are presented in section 2. The gripper design, construction and static testing are presented in section 3. Also, the gripper control electronics (open, close, motor torque limiting) and the main controller programming (autonomous operation and communications) have been constructed and tested with excellent results as part of proof of concept and are presented in section 3. Conclusions follow in section 4.

2 Autonomous Vehicle and Arm Design

A previous design (Marinis, 2009) for the collection of recyclable objects (made of wood or metal) from the ground, has been redesigned to accept a different robotic arm and improved gripper in order to harvest sensitive agricultural products at a height of one meter above “ground level”. The modular design concept and the autonomous operation control electronics remain the same.

2.1 Vehicle Design

The vehicle’s specifications are: Maximum occupied space 1x1x1m with the robotic arm retracted, two sets of wheels (left side – right side) powered by two separately controlled DC motors to provide forward movement, reverse, as well as minimum turning radius (on-the-spot turning), maximum speed of 5 km/h at 5% incline and maximum weight (fully loaded) of 200Kg.

The vehicle shown in Fig. 1 will operate autonomously, powered by on-board 12V batteries and will move independently avoiding obstacles (Marinis, 2009). It will search for products to be harvested and will locate itself suitably for the arm and gripper to proceed with harvesting.

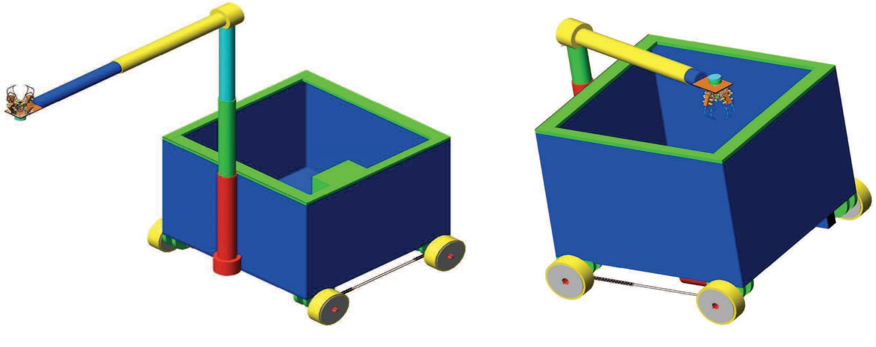

Fig. 1. Empty vehicle with extended and retracted arm and gripper.

2.2 Robotic Arm Design

The robotic arm's specifications are: Maximum height 2m from ground level, contracted height 1m above wheel base, maximum horizontal reach 1.5 m. The minimum operational functionality is: A three dimensional camera system for locating the product to be harvested (not currently developed) will communicate the coordinates to the main controller. The wheel controller will move the vehicle to the closest location and the robotic arm will extend to harvest and retract to store the product. The detailed design and construction of the robotic arm will commence after the collection of data from in-the-field static testing of the gripper.

However, there is a preliminary design of a 5-link robotic arm for this purpose. The gripper is the fifth link. The first link is fastened at the origin (O_0) and can rotate (θ_1) about the Z_1 axis by 360 degrees. The second link extends linearly upwards (by d_1) in three sections. The third link extends linearly (by d_3) in two sections. The fourth link rotates (θ_4) about the Z_3 axis by 360 degrees. The fifth element is the gripper which has a fixed length of 0.3 m. System of axis, prismatic (d) and revolute (θ) variables are defined as in Fig. 2. The origin (O_0) of X_0, Y_0 and Z_0 is located at the base of the vehicle, front side, and center. This is the design's fixed support.

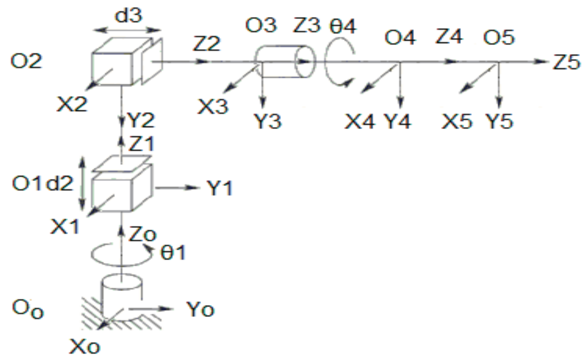

Fig. 2. Preliminary design of the 5-link robotic arm.

Some assumptions were made: The mass of the motors is included in the link mass and each link is assumed to have its center of rotation at ½ the length of the link (as it could have been without the addition of the motor). The mass of the gripper changes from "empty" to "empty + product", which is a variable. Its maximum design mass will be set to 3Kg.

The forward (or configuration) kinematic analysis of the arm was based on the Denavit – Hartenberg convention. Equation 1 shows the derived forward kinematic equations matrix.

After detailed work and simplification of the equation terms, the velocity kinematics analysis yielded the Jacobian matrix of equation 2.

$$T_5^0 = A_1 * A_2 * A_3 * A_4 * A_5 = \begin{bmatrix} c\theta_1 * c\theta_4 & -c\theta_1 * s\theta_4 & -s\theta_1 & -s\theta_1 * (d_5 + d_4 + d_3) \\ s\theta_1 * c\theta_4 & -s\theta_1 * s\theta_4 & c\theta_1 & c\theta_1 * (d_5 + d_4 + d_3) \\ -s\theta_4 & -c\theta_4 & 0 & d_2 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{(1)}$$

$$J = \begin{bmatrix} J_v \\ J_\omega \end{bmatrix} = \begin{bmatrix} -c\theta_1 * (d_3 + d_4 + d_5) & 0 & -s\theta_1 & 0 & -s\theta_1 \\ -s\theta_1 * (d_3 + d_4 + d_5) & 0 & c\theta_1 & 0 & c\theta_1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -s\theta_1 & 0 \\ 0 & 0 & 0 & c\theta_1 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \textbf{(2)}$$

2.3 Autonomous Operation Design

The batteries, electric circuits and control electronics will be installed inside the vehicle in modular form. The electronic boards will be powered by a separate, smaller battery. All communications with external PCs for programming, data acquisition, etc will be via serial interface. Other ad-hoc communication (status, start/stop, etc) during autonomous operation will be via a wireless link (X.25).

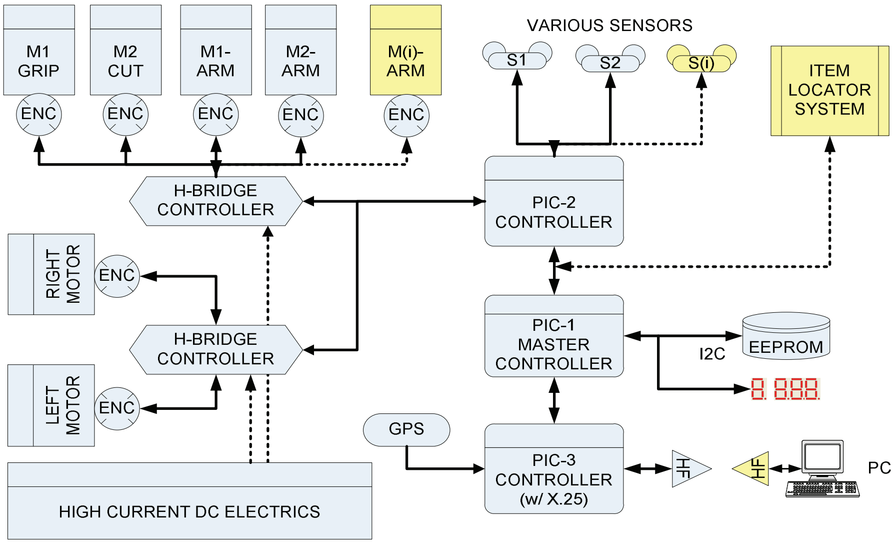

Fig. 3. Block diagram of control and communication electronics.

The block diagram of Fig. 3 is a general plan of the on-board electronics. The "item locator system" will be added later.

The main on-board electronics will control the vehicle's wheels, robotic arm movement, gripper action and communication with other boards. It will also communicate ad-hoc with a human supervisor (remotely located PC with X.25 capability). This modular approach allows for future experimentation/testing.

The additional boards will receive signals from inexpensive ultrasonic sensors/camera and send mobility information to the wheel controller. A three dimensional camera system will locate the product to be harvested and will send location information to the arm and gripper controller. Sensitive information such as current status, operation in progress and statistical data will be saved in non-volatile EEPROM.

2.4 Proof of Concept

Initial testing of individual systems has proved the design concept. All PIC controllers (1, 2 and 3) have been programmed and tested successfully (excluding the arm movement procedures). Programming of the robotic arm controller will commence when the forward kinematics of the arm are combined with prototype link dynamics and selected motor data. Final programming will follow the construction and testing of the prototype arm. Additional hardware (board and 2-way VHF radios) was used in testing X.25 wireless communication. Initial proof of concept programming for the gripper's EEPROM saved data as well as main MCU communications has been successful.

3 Gripper Design

The system is comprised of a mechanical robotic end-effector utilizing a set of four "fingers", an electric motor and motor controller as well as the dedicated control electronics board. Power is supplied from the on-board batteries. Different sets of fingers will change the overall gripper's geometry to suit for harvesting different size fruits. They may also utilize different fruit-contact material for a more sensitive crop.

3.1 Specifications and Mechanism Design

The geometry and function of the first set of fingers was designed to enable the capture of products of spherical shape and sizes of 20mm up to 100mm in diameter. With the gripper in the upright position (as in Fig. 1), it should hold a captured weight of not less than 400g (1Kg effective) while in rapid robotic arm motion. The contact materials covering the fingers must be approved for food handling.

Three common types of mechanisms were initially considered: Two-fingered parallel jaw, scissor-type and vertical grippers, but they did not offer good capturing results. The gripper has four moving "fingers" which pivot up to 50 degrees each to allow a maximum opening diameter of 150 mm among them. This will allow the robotic arm to operate within a 25mm maximum positioning error.

The initial design of the gripper’s fingers involved the use of four solid pieces of plastic, bent properly to capture spherical objects and is shown in Fig. 4.
The design of the moving parts allows their easy replacement in case of wear or damage. However, soon after construction and initial testing they proved to have an inherent degree, however small, of harsh handling some sensitive fruit. Also, smaller items tended to “escape” the gripper from between adjacent fingers.

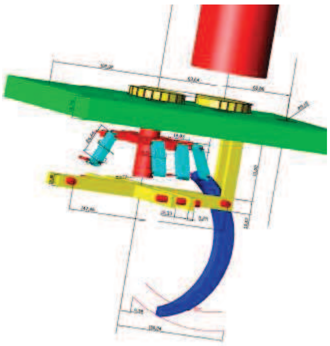

Fig. 4. Initial design of the gripper’s “fingers” with provision for a speed reduction gear set.

Revisions in the original design yielded the prototype gripper shown in Fig. 5. It is supported vertically using two angled metal supports in order to test the mechanical functionality and static performance of the design, as well as to allow development of the controller electronics.

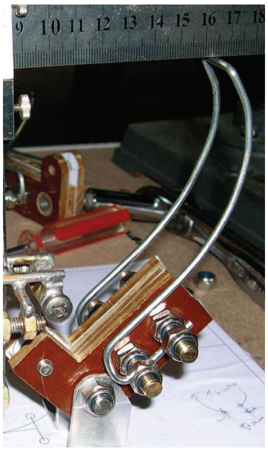

Fig. 5. Redesigned gripper’s fingers and construction of prototype.

The fingers have a two-section design in order to maintain the stiffness of the top half and allow a flexible wire fingertip as shown in Fig. 5. This has two additional advantages: The void between two consecutive fingers is greatly reduced and the lower part can be easily interchanged and inexpensively replaced in case of wear or modification of mission (or operating environment). Fingertips of different geometry or material can be attached.

3.2 Description and Operation

All parts are fastened on a single board, secured by two iron angled supports (for static testing). Above it, there is a 10V, 340mA bipolar step motor connected to a multi-turn high accuracy potentiometer through a set of reduction gears (for fingertip position reporting). The motor turns a screw and nut combination to provide linear motion to four links below the board. The links move the top of the four fingers up or down, pivot them about four fixed points and cause them to open and close. The top part of each finger is made of solid material (Bakelite) and provides four points to secure a loop of bent galvanized steel wire (fingertips) as shown in Fig. 5. This wire captures the product.

A standard step motor controller with dual H-bridge electronics has been modified to open and close the fingers. The PIC controller on the board has been replaced with another, programmed for adjustable closing torque, fast/slow movement, reset, automatic position calibration, position encoding/decoding and general communication with higher level modules. Motor torque is controlled by limiting the maximum current through the motor's windings using PWM. Additional circuit modifications have been made to this effect. The torque level (which sets the PWM percentage) is communicated by the farmer to the master controller when the command to start harvesting is sent. The level depends on previous results from harvesting of the specific crop.

A step motor is used because it can produce a high holding torque without changing its position and consequently the pressure applied to the captured product. Power to the motor (only) is provided from the main 12V batteries.

Separate electronics (PIC 18F452) control the higher level functions of the gripper. This controller (PIC-1) communicates via RS232 to accept commands, report status and adjust the closing torque setting of the step motor board. The extent of the fingertip opening has a specified maximum but the controller adjusts the maximum number of turns of the motor based on the size of the fruit and the geometry of the attached set of fingertips by means of a look-up table stored in EEPROM. This also changes the range of values expected from the feedback potentiometer. All operational data is stored in EEPROM via I2C for automated recovery from a power shortage and also for debugging.

The other controller (PIC-2) handles all inter-module communication. All PIC code is written in C language using structured programming techniques.

3.3 Gripper Testing

The gripper was tested statically, based on the types of damage that can be caused to a harvested fruit shown in Table 1. The torque level (PWM percentage) was tested for some tested fruit to determine the maximum safe value for each. The results that followed were excellent. It is assumed that no further damage is caused from the fruit's own weight (too ripe to handle).

Table 1. Types of possible damage effected to sensitive harvested items.

Type of damage	Cause
1. Crushing or splitting	Excessive force
2. Superficial grazing of the skin	Contact material
3. Visible internal bruising	Excessive force
4. Internal bruising (not visible)	Collection bin / handling
5. Other handling operations damage	Collection bin / handling

The final design was tested statically on angled metal supports. The opening and closing geometry of the gripper remained unchanged after repeated operations. Fig. 6 shows a problem when using fingertips of larger size where the targeted fruit (or adjacent fruit) can get caught between the fingers. Tested products were repeatedly captured successfully and without damage, as shown in Fig. 7. Of course, the smaller item would have been better served using fingertips of a smaller size. The fingertips made of steel wire performed far better than the initial solid design. The lack of sharp edges, the large area of contact with the product and the geometry of the closing motion provided excellent results.

When testing at full motor torque (no limiting of the motor's current) all tests damaged all tested fruit. In another test, when a solid object was inserted to block the gripper's closing action, there was no damage to the gripper due to the flexibility of the wire fingertips.

A problem arose when collectable fruit were picked from a pile (close group). In this case, two items were mistaken for one, and in an effort to collect them, they were not securely captured on the first attempt. One ripe item fell off due to shaking the pile. During dynamic testing, if the gripper's electronics indicate a failed capture, the harvesting approach will be slightly modified and a second harvesting attempt will commence. Further adjustments and attempts (if any) should relate to the method of locating the items, otherwise the specific targeted fruit should be dismissed.

Fig. 6. The fingertip geometry is much larger than the fruit size.

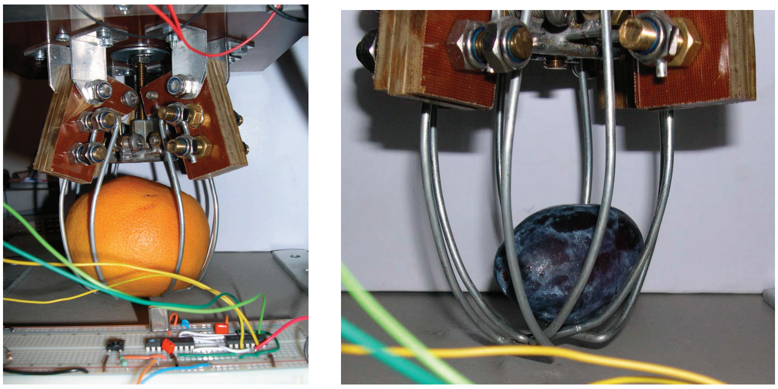

Fig. 7. Successful capturing of sensitive items (large and small).

4. Conclusions

This paper presents an effort for the design of the prototype of an autonomous vehicle with a "five link" robotic arm and the development of a suitable gripper.

The gripper was designed, and, its prototype was constructed and tested (statically) for its effectiveness in collecting fruits of size suitable to the fingertips used, without damaging them. The gripper encloses-captures instead of squeezing-capturing the fruit which results in minimized damages, by design. Electronic circuit boards were constructed with appropriate control and their initial programming was successfully implemented for the gripper's operation. The robotic arm and related electronics are in the design phase.

Further gripper-related research will be directed in the development of a cutting mechanism, possibly attached at the tip of the gripper. Additional electronics will provide for the vehicle's roaming and the fruit locator system.

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