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Optimal Design of a Cucumber Harvesting Robot

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Abstract

This paper presents a procedure and the results of an optimal design of the kinematic structure of a manipulator to be used for autonomous cucumber harvesting in greenhouses. The design objective included the time needed to perform a collision-free motion from an initial position to the target position as well as a dexterity measure to allow for motion corrections in the neighbourhood of the fruits. The optimization problem was solved using the DIRECT algorithm implemented in the TOMlab package. For cucumber harvesting four degrees-of-freedom, *i.e.* three translations and one rotation around the vertical axis, are sufficient. The results indicate that a four link PPRR type manipulator is most suitable for harvesting cucumbers. Although computationally expensive, the methodology used in this research was found to be powerful and offered an objective way to evaluate and optimize the kinematic structure of a robot to be used for cucumber harvesting.

1. Introduction

In 2001 a 5 years research project on autonomous cucumber harvesting was concluded with a successful field test of the harvesting robot in a research greenhouse (Van Henten *et al.*, 2002, 2003b). At the beginning of this project, the choice of the manipulator for the harvesting robot was based on an empirical qualitative analysis of the working environment and the task to be performed. This process is illustrated in Figure 1. Main design criteria were the ability of the robot to reach cucumbers within a predefined greenhouse volume, its size because of the limited workspace and the possibility of collisions with plants and greenhouse structure, its weight carrying ability, speed and the ability of the machine to operate in adverse climate conditions with high temperature and humidity levels.

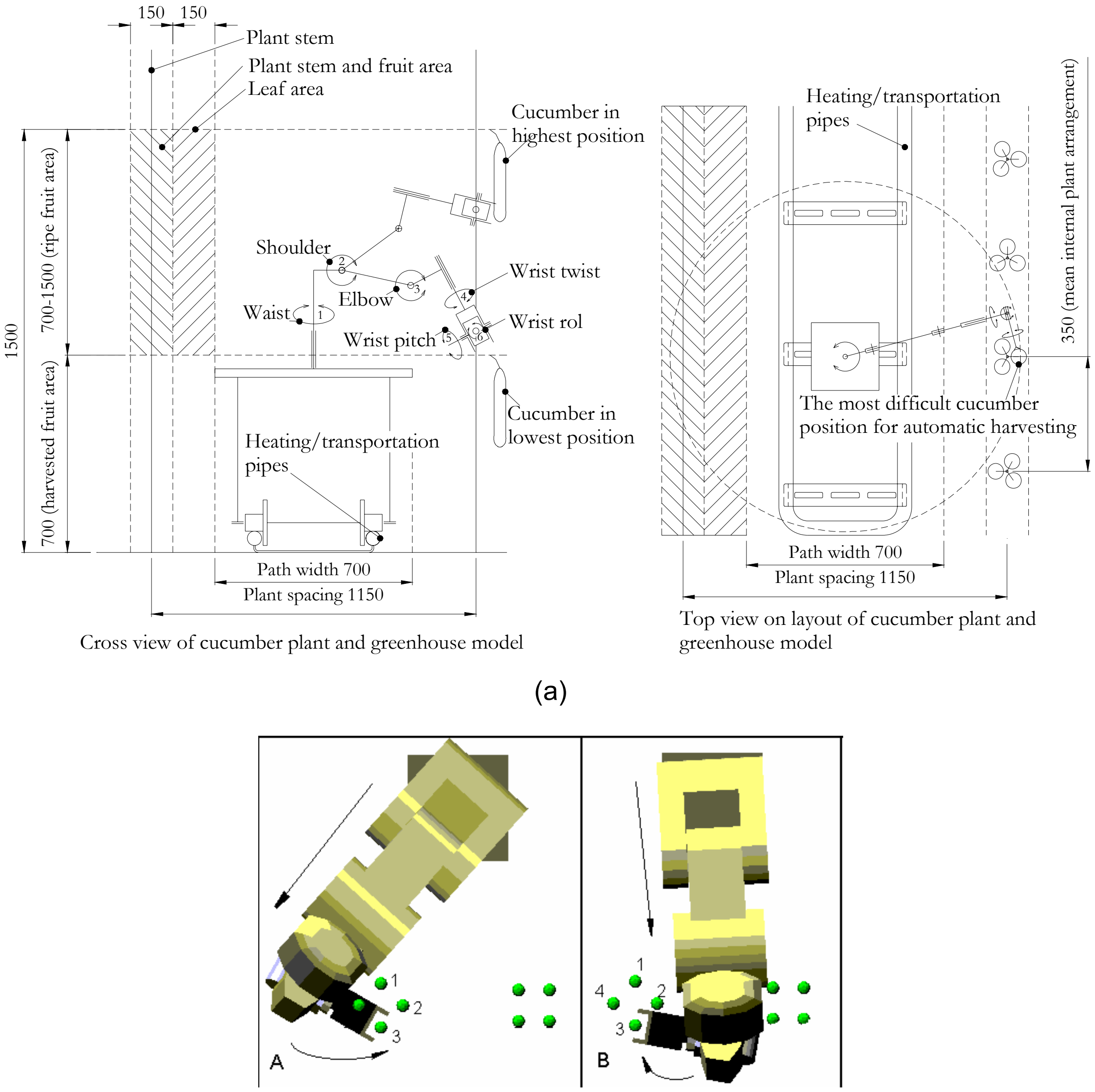


Figure 1. Manipulator choice based on two-dimensional (a) and quasi-three-dimensional (b) models of the working environment of the harvesting robot.

Two-dimensional and three-dimensional models were used to evaluate various manipulator structures with respect to the harvesting task it should perform. As a result of this empirical analysis, a manipulator was chosen consisting of 7 links: a linear slide (*i.e.* a prismatic link) on top of which a Mitsubishi RV-E2 manipulator with 6 rotating links was mounted. This platform offered abundant flexibility for research and development during the initial phases of this project. Once the functional model of the harvesting robot had demonstrated the feasibility of fully autonomous harvesting of cucumber fruits in a greenhouse (Van Henten *et* *al.*, 2003b), ways were investigated to improve the speed and success rate of this robotic system. During the field tests of the harvesting robot it was found that four degrees of freedom, *i.e.* three translations and one rotation, were sufficient to harvest a cucumber. For this task, the 7-link manipulator used was overly complex. Using quantitative measures and non-linear optimization techniques, in a simulation study, optimal redesign of the manipulator was pursued. This paper presents an outline of the methodology used in this design study and a summary of the results obtained.

2. Methodology

The optimization problem studied in this research was to determine an optimal manipulator design represented by the set of design parameters $\mathbf{p}^*$, such that

$$\mathbf{p}^* = \inf_{\mathbf{p}} O(\mathbf{p}) \tag{1a}$$

subject to inequality constraints of the form

$$\mathbf{p}_{\min} \leq \mathbf{p} \leq \mathbf{p}_{\max} . \tag{1b}$$

Here O is a suitably defined objective function. Basically, the set of design parameters $\mathbf{p}$ may include all kinematic design parameters of the robot such as the number of links, the type of links (prismatic (P) or rotational (R)) and, dependent on the type of the link, a subset of the Denavith-Hartenberg parameters θ, α, a and d associated with each link. See Craig (1989) for a definition of these Denavith-Hartenberg parameters. If a link includes a rotational joint, the joint angle θ is a control variable used to steer the joint and is not explicitly optimised. Then link twist α, the link length a and the link offset d can be varied continuously to search for the best value of the objective function of the kinematic design. If a link is prismatic, d is a control variable used to steer the joint. In that case, θ, α and a can be varied continuously during an optimisation. If the number and/or type of links is varied, the optimisation problem combines both discrete values (the number and/or type of links) and continous values (the link parameters). Clearly, all variables can be restricted to lie within bounded regions to represent, for instance physical design limits, expressed by the inequality constraint (1b).

For autonomous cucumber harvesting the design requirements were defined as follows. First of all, a cucumber harvesting robot has to operate in a tight working environment as illustrated in Figure 1 and the manipulator structure should be such that, during the manipulator motions, collisions of the manipulator with the canopy, the greenhouse structure and other parts of the robot are prevented. Secondly, to be economically feasible, the cycle time of a single harvest operation should not exceed 10 s (Bontsema *et al.*, 1999). This includes fruit detection, ripeness assessment, 3D localisation of the fruits, motion planning, the motion of the end-effector to the fruit, gripping and cutting of the fruit and the return motion to the crate. To satisfy this performance requirement, the motion trajectory of the manipulator should be as short as possible. Finally, the manipulator should have maximum dexterity once the tool-centre-point (TCP) has arrived at the picking position. Dexterity is a measure quantifying the ability of a manipulator to move and rotate the TCP in all directions. On the harvest robot, a camera mounted on top of the end-effector may be used for final alignment of the end-effector with the fruit stalk in case of inaccurate positioning information from the main camera system of the robot (Van Henten *et al.*, 2002). Therefore, considerable dexterity is needed to be able to make the required corrections to the position and orientation of the end-effector.

The objective function used in this research was:

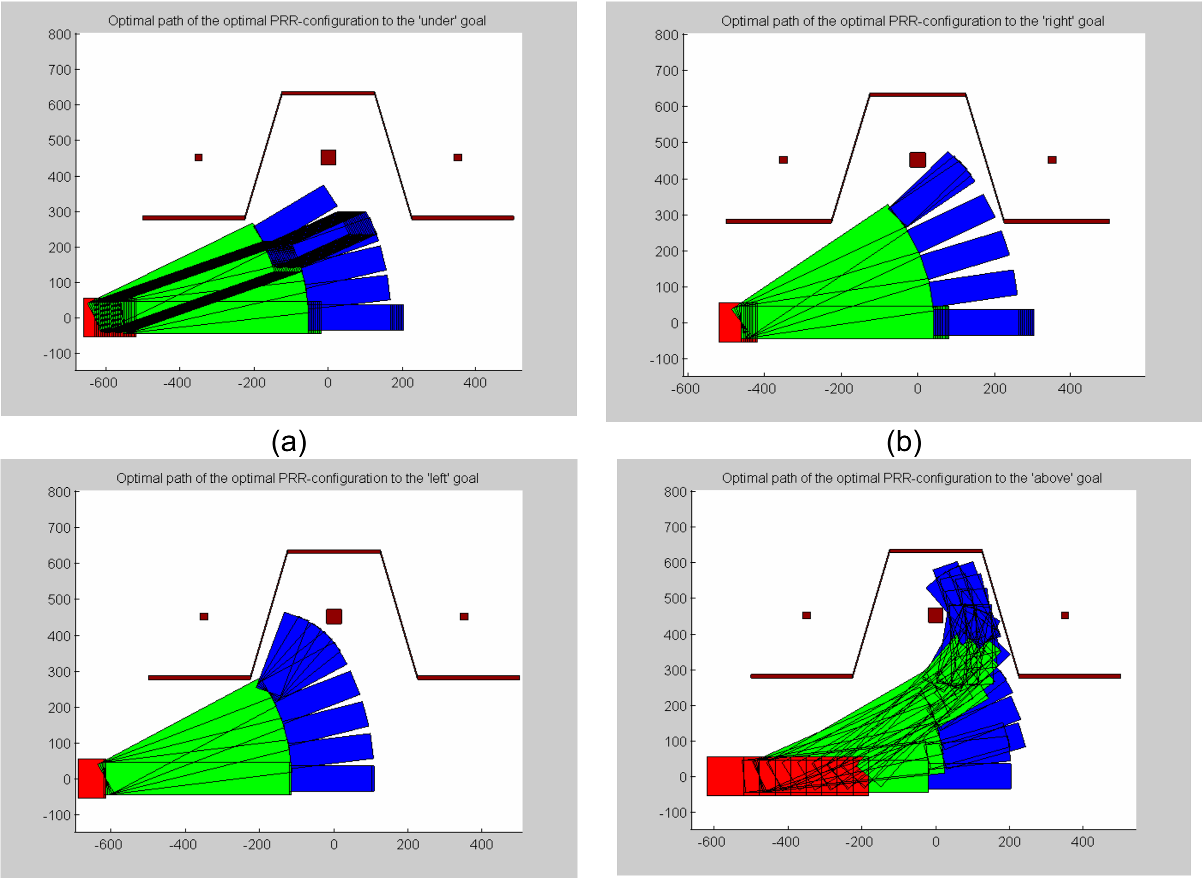
$$O(\mathbf{p}) = \sum_{k=2}^{N} \sqrt{(\mathbf{y}_k - \mathbf{y}_{k-1})\mathbf{A}(\mathbf{y}_k - \mathbf{y}_{k-1})^T} + \frac{1000}{\sqrt[2m]{\det\left(\mathrm{J}(\mathbf{y}_N)\mathrm{J}(\mathbf{y}_N)^T\right)}} \qquad (2)$$

in which the first part expresses the path length of the *N*-step manipulator motion through the configuration space and the second term expresses the dexterity of the manipulator at the harvest position. Here, $\mathbf{y}_k$ is the k-th configuration of the *N*-step manipulator motion, A is a weighting matrix, J is the Jacobian and m is the number of degrees of freedom. The weighting factor of 1000 balances the contribution of the two different objectives to the final performance criterion. This value was determined empirically. The A^*-algorithm was used to produce the shortest possible collision-free manipulator motion to perform the required task (Van Henten, 2003a). Because the optimization problem was expected to contain local minima, in this research the DIRECT algorithm implemented in the TOMlab package was used (Jones *et al.*, 1993).

3. Results

Cucumbers grown in a high-wire cultivation system almost all have a distinct vertical orientation, therefore four degrees of freedom, *i.e.* three translations and one rotation will suffice for harvesting. Based on this observation, to reduce complexity, in this case study only motions in the horizontal plane were considered and the optimization was restricted to three links. For vertical motions, a prismatic link might be added at a later stage.

In this case study, for the first link a prismatic link was used, motivated by the fact that a robot will have to move over a path parallel to the plants. This motion is effectively represented by a prismatic link. This leaves a choice of a prismatic or rotational joint for the second and third manipulator links.



(a) (b)

(c) (d)

Figure 2. Manipulator motions of the optimal PRR robot to four picking positions in front of the cucumber stem (a), to the right of the stem (b), to the left of the stem (c) and behind the cucumber stem (d).

The workspace model for which the manipulator was developed is shown in Figure 2. It shows a top view of an artificial greenhouse environment in which the squares represent the stems of the cucumber plants located approximately 350 mm from each other. The wall around the cucumber stem in the centre is a virtual construction used in the optimization to restrict manipulator motions to prevent collisions with objects in the workspace. The manipulator should be able to harvest cucumbers located in front, to the left and to right of the main stem as well as hanging behind the stem. This is illustrated in Figure 2 as well.

Optimal manipulator design was implemented in two steps. First, three manipulator configurations, *i.e.* PRR, PRP and PPR, were optimized for the four individual harvest positions located around the cucumber stem. Evaluated over all four harvest positions, the PRR design showed the best performance. Each of the 12 optimizations took several hours on a Pentium III machine. Then, secondly, a PRR manipulator was optimized for all four harvest positions together. Parameters to be optimized in this case were the initial position of the second prismatic link as well as the lengths of the two rotational links. Motion trajectories of the optimal design of this PRR manipulator to all four harvest positions are shown in Figure 2. To assure collision-free motions as well as dexterity at the harvest position, the optimized final link is shorter than the previous link. In all cases, the manipulator effectively moves to the target without colliding with objects in the workspace. This optimization took about three days on a Pentium III machine. Combining these results with the earlier assumption that vertical motions are effectively dealt with by a prismatic link implemented as first or second link, this study suggests that a PPRR manipulator is an effective configuration to perform the task of harvesting cucumbers.

4. Conclusions

The methodology used in this research was found to be powerful and offered an objective way to evaluate and optimize the kinematic structure of a robot to be used for cucumber harvesting. By doing so, it prevented a cumbersome and limited trial and error process. However, this approach is computationally (very) expensive.

The results indicate that a four link PPRR manipulator is an effective configuration to perform the task of harvesting cucumbers. Compared with the 7 link P6R robot used in the research prototype of the cucumber harvester, this means a considerable reduction in complexity and cost which is an important issue when application in horticultural practice is considered.

Acknowledgements

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