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# Analysis of a motion planning problem for sweet-pepper harvesting in a dense obstacle environment

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To reach a fruit in an obstacle-dense crop environment, robotic fruit harvesting requires a collision-free motion of the manipulator and end-effector. A novel two-part analysis was conducted of a sweet-pepper harvesting robot based on data of fruit ($N = 158$) and stem locations collected from a greenhouse. The first part of the analysis compared two methods of selecting the azimuth angle of the end-effector. The new 'constrained-azimuth' method avoided risky paths and achieved a motion planning success similar to the 'full-azimuth' method. In the second part, a sensitivity analysis was conducted for five parameters specifying the crop (stem spacing and fruit location), the robot (end-effector dimensions and robot position) and the planning algorithm, to evaluate their effect on successfully finding a collision-free goal configuration and path. Reducing end-effector dimensions and widening stem spacing are promising research directions because they significantly improved goal configuration success, from 63% to 84%. However, the fruit location at the stem is the strongest influencing parameter and therefore provides an incentive to train or breed plants that develop more fruit at the front side of the plant stem. The two analyses may serve as useful tools to study motion planning problems in a dense obstacle environment.



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## 1. Introduction

Robotic fruit harvesting is motivated by social, economic, environmental and food quality aspects (Lewis, Watts, & Nagpal, 1983). The need to reduce the production costs is a prominent motivator to automate harvesting in high-value crops such as tomato, cucumber or sweet pepper. Harvesting these crops is challenging given the complex working environment for the robot that comprises varying poses, sizes, shapes and colours of fruit and other objects (Bac, Van Henten, Hemming, & Edan, 2014). Furthermore, a target fruit can be surrounded by densely spaced obstacles, i.e. plant parts, support wires, and fruit clusters. The manipulator and end-effector need to avoid these obstacles to successfully approach a target fruit and prevent damages to the plant or nearby fruit. Successful planning and implementation of the manipulator motion determines the feasibility of robotic harvesting, and therefore it could be useful to understand the influence of various parameters affecting motion planning success.

Motion planning has received attention in literature on autonomous crop harvesting. Work reported ranges from simple manipulator control and kinematics to advanced motion planning (Edan, Rogozin, Flash, & Miles, 2000; Guo, Zhao, Ji, & Xia, 2010; Hannan & Burks, 2004; Kondo, Nishitsuji, Ling, & Ting, 1996; Kondo et al., 2007; Liang & Wang, 2010; Sakai, Iida, Osuka, & Umeda, 2008; Sivaraman & Burks, 2006; Van Henten, Hemming, Van Tuijl, Kornet, & Bontsema, 2003; Van Henten, Schenk, van Willigenburg, Meuleman, & Barreiro, 2010; Van Willigenburg, Hol, & Van Henten, 2004). Some papers conducted an in-depth analysis of the manipulator kinematics (Sivaraman & Burks, 2006; Van Henten, Van't Slot, Hol, & Van Willigenburg, 2009). The influence of the crop structure on the success rate of generating successful harvest grasp poses for the manipulator was also analysed (Van Henten et al., 2010). However, to date, analyses of motion planning success in relation to various parameters involved (design of end-effector, planning algorithm, crop environment) have not been reported.

The current work attempts to fill this gap for the field of fruit harvesting, by an analysis for sweet pepper. Additionally, the paper may contribute to the field of robotics at large. Sensitivity analysis is not a commonly used instrument for performance analysis of robotic systems. Some examples include sensitivity analysis focussing on improving trajectories (de Luca, Lanari, & Oriolo, 1991), comparing robot designs (Tannous, Caro, & Goldsztejn, 2014), or positioning errors of the end-effector (Zhang, Ba, & Mu, 2012). These studies mostly concentrated on the influence of robot parameters. The current research will extend the analysis beyond the robot design to consider parameters of the planning algorithm, and of the crop, i.e. the working environment of the harvesting robot.

To provide a realistic case study for the analysis of motion planning for autonomous sweet pepper harvesting, measurements were collected of the three-dimensional (3D) shape of a crop grown in a greenhouse. In the 3D working environment generated with these data, simulations were performed with a model of the harvesting robot developed for the crop. The analysis contained essentially two steps. Firstly, the analysis focussed on the effect of the angle of approach of the end-effector, to the fruit, on the motion planning success. Then, secondly, building on these results, a sensitivity analysis was performed in which the effect of end-effector size, the robot position, a parameter of the motion planning algorithm as well as parameters determining the crop environment (fruit location and stem spacing), were evaluated. The methodology and results may also provide insights for motion planning in other high-value crops.

## 2. Components of the motion planning problem

The robot used was developed as part of the research project CROPS 'Clever Robots for Crops' (CROPS, 2014). Section 2.1 details this robot, Section 2.2 describes the crop row used and Section 2.3 describes the algorithms used to address the motion planning problem.

### 2.1. Robot

The robot consisted of a platform, a manipulator and an end-effector (Fig. 1). The platform developed (Jentjens Machinetechniek B.V., The Netherlands) used the heating pipes of the greenhouse as a rail system to travel along the crop row. Hemming et al. (2014) describe more details about the robot.

The manipulator (Technical University Munich, Germany) comprised nine degrees-of-freedom (DOF). The first joint was prismatic, whereas the other joints were rotational. Transformations were derived between the links (Table 1), using the modified Denavit–Hartenberg convention introduced by Craig (2004), where $a_{i-1}$ refers to the link length (m) of link $i$, $\alpha_{i-1}$ refers to the link twist (rad) of link $i$, $d_i$ refers to the link offset (m) of link $i$, and $\theta_i$ refers to the joint angle (rad) at axis $i$ (Table 1).

Manipulators used for fruit harvesting typically consist of two to seven DOF (Bac, Van Henten, et al., 2014). An advantage of using many DOFs is an improved target-reachability in cluttered environments. However, the disadvantage is that common motion planning algorithms have difficulty in finding a collision-free path within a reasonable time. Furthermore, additional DOFs decrease speed (the stiffness reduces, which imposes lower motor torques to avoid vibrations) and reliability, and increase the cost of the manipulator.

The end-effector grasps the fruit using a suction cup and subsequently cuts the peduncle (Fig. 2), which is the connecting stem between the fruit and main stem. The bounding box of the end-effector had dimensions of 170 mm (width), 260 mm (length), and 110 mm (height). More details about the end-effector are described in the patent (Van Tuijl & Wais, 2014).

### 2.2. Crop row

#### 2.2.1. Measurements in the greenhouse

A total of 60 plant stems, and 165 attached fruit, were recorded from a crop row (sweet-pepper cultivar: Waltz) grown in a commercial greenhouse in the Netherlands. Only hard obstacles (fruit, stem, support wire, robot) that may cause

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