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Integration of perception capabilities in gripper design using graspability maps

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Agricultural environments impose high demands on robotic grippers since the objects to be grasped (e.g., fruit) suffer from inherent uncertainties in size, shape, weight, and texture, are typically highly sensitive to excessive force, and tend to be partly or fully occluded. This paper presents a methodology for evaluating the influence of perception capabilities on grasping and on gripper design using graspability maps. Graspability maps are spatial representations of grasp quality grades from wrist poses (position and orientation) about an object and are generated using simulation. A new module was developed to enable the insertion of object pose errors for testing the effects of perception inaccuracies on grasping. The methodology was implemented for comparing two grippers (*Fin-Ray* and *Lip*-type) for harvesting two sweet-pepper cultivars. A 3D model of each gripper was constructed and suitable grasp quality measures were developed and validated in a physical environment. Task and gripper-specific grasp quality measures were developed for each implementation. Sensitivity analyses included varying pepper dimensions and perception inaccuracies. These were followed by analyses of the influence of gripper design parameters on grasp capabilities. Results indicate that the *Lip-type* gripper is less sensitive to inaccuracies in object orientation, while both grippers are similarly sensitive to inaccuracies in object position. Specific perception system demands and design recommendations are given for each gripper, and cultivar. The results illustrate the importance of integrating perception analysis in the gripper design phase and the utility of the graspability simulation tool for design analysis.

1. Introduction

Grippers are a critical component in robotic systems required to perform object manipulation. They must be appropriate for the robotic arm, the object to be grasped, the environment in which the system operates, and the task at hand. While standard mechanical structures are typically used for robotic manipulators, grippers are typically re-designed for each implementation. Thus, gripper design is an important part of

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Nomenclature

TPR	True-Positive Rate
FPR	False-Positives Rate
TP	True-Positive
FP	False-Positive
FN	False-Negative
TN	True-Negative
NL	Netherland's
IL	Israel
FCA	force closure angle
SD	stability distance
CVR	cylinder voxel rate
Q_{LIP}	quality measure used for the *Lip*-type gripper
Q_{BFS}	quality measure used for the *Fin-Ray* gripper

robotic system design. A well designed gripper can contribute to successful system operation, increase overall system reliability, simplify requirements from other system components, and decrease system implementation costs (Brown & Brost, 1997; Raghav, Kumar, & Senger, 2012).

Previous research on gripper design suggested six main guidelines (Zaki, Soliman, Mahgoub, & El-Shafei, 2010): minimize gripper weight, grasp object securely, multiple object gripping with a single gripper, fully encompass the object within the gripper, do not deform the object, and minimize size taking into account proper object-gripper interaction. In many cases there are interactions between these different guidelines. Current gripper design methodologies try to optimize gripper kinematics (Ciocarlie, Hicks, & Stanford, 2013; Li, Liu, Li, & Li, 2008) and dynamics (Blanes, Mellado, Ortiz, & Valera, 2011; Cao, Gu, Li, & Liu, 2013) taking into account object constraints (e.g., size, shape, weight, slipperiness, fragility, and accessibility) and task constraints (force and motion) (Blanes et al., 2011; Zaki et al., 2010). Design approaches include empirical methods (Chelpanov & Kolpashnikow, 1986; Giannaccini, Dogramadzi, & Pipe, 2011; Sam & Nefti, 2011; Spiers, Baillie, Pipe, & Persad, 2012), and objective functions optimizing geometric parameters, e.g., capability index, or grasping index (Berman & Nof, 2011; Brown & Brost, 1997; Cutkosky, 1989; Gorce & Fontaine, 1996; Saravanan, Ramabalan, Ebenezer, & Dharmaraja, 2009; Streusand & Turner, 2011; Walsh, 1984).

The gripper design process is also influenced by the manipulation abilities of the robotic-gripper system which are also highly dependent on the capabilities of the sensory system. The task of the sensory system is to provide the geometric description of the objects within the environment (Fantoni, Gabelloni, & Tilli, 2012). Although there is a vast body of literature that links grasping to perception (Coelho, Piater, & Grupen, 2001; Detry et al., 2011; Moreno, Hornstein, & Santos-Victor, 2011), their interactions have been addressed in the context of grasp planning and control and not at the design phase. However, gripper design highly influences both motion planning and control (Boubekri & Chakraborty, 2002; Ceccarelli, Figliolini, Ottaviano, Mata, & Criado, 2000), thus it is important to address the perception-action links during design. For example, pepper harvesting requires cutting the pepper's stem at the peduncle without harming the fruit or the plant. Hence, the accuracy with which the fruit pose (position and orientation) and peduncle can be detected determines the operation possibilities of the gripper and imposes constraints on gripper design.

One of the major challenges in the development of a selective harvesting robot is how to grasp, detach, and manipulate the fruit without damaging it or the plant (Edan, 1999). Gripper design has been addressed in many agricultural robotics research and development projects, e.g. harvesting of tomatoes (Ceccarelli et al., 2000; Li, Li, & Liu, 2011; Li, Li, Yang, & Wang, 2013; Ling et al., 2004; Monta, Kondo, & Ting, 1998), melons (Edan, Haghighi, Stroshine, & Cardenas-Weber, 1992; Wolf, Bar-Or, Edan, & Peiper, 1990), apples (Baeten, Donné, Boedrij, Beckers, & Claesen, 2008; De-An, Jidong, Wei, Ying, & Yu, 2011), cucumbers (van Henten et al., 2002), asparagus (Irie, Taguchi, Horie, & Ishimatsu, 2009), grapes (Monta, Kondo, & Shibano, 1995), cabbages (Murakami, Otsuka, Inoue, & Sugimoto, 1995), cherries (Tanigaki, Fujiura, Akase, & Imagawa, 2008), strawberries (Hayashi et al., 2010), radishes (Foglia & Reina, 2006), peppers (Hemming, Bac, et al., 2014; Hemming, Ruizendaal, Hofstee, & van Henten, 2014; Hemming, van Tuijl, Gauchel, & Wais, 2014; Kitamura & Oka, 2005; mushrooms, Reed, Miles, Butler, Baldwin, & Noble, 2001), and in a similar context on grippers for food products (Blanes et al., 2011; Chua, Ilschner, & Caldwell, 2003; Pettersson, Davis, Gray, Dodd, & Ohlsson, 2010),

Fruit detection algorithms for robotic applications have been extensively studied (Kapach, Barnea, Mairon, Edan, & Ben-Shahar, 2012) and specifically recently in a parallel study for sweet pepper detection (Hemming, Ruizendaal, et al., 2014), however linking perception into the gripper design process has not been investigated. While perception is a critical element in most environments, in agricultural environments its importance is amplified due to inherent complexities (e.g., occlusions, and dynamic lighting conditions) and uncertainties (e.g., highly variable fruit size, shape, and location) caused by the natural biological variability. The current research suggests a methodology for evaluating the effects of perception capabilities during the mechanical design of the gripper, i.e., prior to full system integration. The method is based on a simulation tool developed to analyse the influence of perception errors on grasp quality based on models of the designed gripper and object to be grasped. Analysing the sensitivity of the gripper design to perception errors can be derived by analysing the effects of errors in object pose estimation on grasp quality using graspability maps. Graspability maps provide an efficient representation of grasp quality grades for grasp poses about the object and have been used for comparison between different grippers (Eizicovits & Berman, 2014a, 2014b; Roa et al., 2014; Roa, Hertkorn, Zacharias, Borst, & Hirzinger, 2011).

The current paper details the building blocks of the proposed methodology and simulation tool, and demonstrates its use with a case study of developing a gripper for sweet-pepper selective harvesting. We demonstrate an evaluation of the influence of perception errors for comparison between two different gripper designs and their parameters. The presented methodology complements the mechanical gripper design methodology developed in a parallel research (van Tuijl, 2015;

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