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Research Paper

Vision-based localisation of mature apples in tree images using convexity

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This paper details a procedure for detecting apples in tree images using shape analysis are presented. The core of the procedure consists of a so-termed *convexity test* that identifies edges that could correspond to three-dimensional convex objects of a given size range from a much larger set of edges. This is achieved by analysing a number of intensity profiles that originate at each edge and determining whether they have a shape that is suitable with a 3D convex object of the correct size. We show that contrarily to the prevailing opinion, the intensity functions of three-dimensional convex objects are not necessarily convex, which led us to developing models for describing such profiles. The simplest suitable model includes four parameters that can be easily estimated by a standard least square constrained optimization procedure. After merging the selected edges that fall on circles, a second analysis is performed to remove false positive detections and eliminate multiple detections of apples. The procedure was demonstrated on 51 grey-level images that were recorded in a Golden Delicious apple variety orchard under natural light conditions. On average, together with preliminary pre-processing operations, the convexity test removed 99.8% of the edges initially identified by Canny filter. Analysis based on the remaining edges led to correct detection of 94% of the apples visible in the images. Fourteen percent of the identified objects were "false positive" detections, mainly due to leaves or parts of leaves that generated convex surfaces very similar to apples, or by leaves that lay on apples and created misleading edges.

1. Introduction

Localisation of fruit on trees is an important and still challenging issue in agriculture, which has potential applications ranging from fruit load estimation to yield forecasting and robotic harvesting. The main objective of this study was to investigate whether the property of convexity of fruit such as apples can be used to find them in complex tree images. Intuitively, it seems unlikely that apple trees contain other convex objects with sizes similar to that of apples. Hence the present paper addresses the question of whether these two properties – convexity and size – are sufficient for locating all apples, and only apples, in an apple tree image.

Automated vision-based localisation of fruit has been studied intensively (see review papers of Jimenez, Ceres, & Pons (2000), Li, Lee, and Hsu (2011)). Although numerous studies focused on approaches based primarily on colour analysis, the major drawback of such approaches is that the

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Nomenclature

a	Scaling parameter
D	Dynamic range of CCD sensor
d	Deviation between chord and actual edge pixels
d_0	Coefficient of diffuse light
d_1	Coefficient of scattered light
d_2	Coefficient of reflected light
E	Approximation error
I	Observed light intensity
L	Length of segment (pixels)
n	Unit vector in direction of normal
$\tilde{n}$	Normal to circle
p	Number of pixels
R	Radius of object to be detected (pixels)
R_{min}	Minimum radius of object to be detected (pixels)
R_{max}	Maximum radius of object to be detected (pixels)
r	Radius of circle formed by intersection of sphere and plane defined by the segment under analysis and the camera (pixels)
U	Illumination
z_c	Z-coordinate of sphere centre (m)
(α, β, γ)	Direction to light source (rad)
Δ_i	Difference between observed and modelled intensities at pixel i
δ	Distance between circle centres (pixels)
Θ	Angle between incoming virtual light source and camera (rad)
Θ_c	Angle between normal to object surface and camera (rad)
Θ_s	Angle between normal to object surface and light source (rad)
Θ_Σ	Angle between normal of the circle and direction to camera (rad)
ρ	Maximum angle between vector from camera to centre of apple and vector from camera to apple edge (rad)
σ	Texture coefficient
φ	Angle between direction to centre and direction under investigation (rad)

fruit apparent colour varies not only depending on variety or physiological stage but also on the illumination, which cannot be controlled in daytime outdoor applications. Quite surprisingly, relatively few studies have considered alternative approaches based primarily on shape analysis, i.e. based on the fact that most fruits are, in first approximation, spherical objects. The first attempts to recognize convex forms in tree images were done 25 years ago (Levi, Fala, & Pappalardo, 1988; Whittaker, Miles, Mitchell, & Gaultney, 1987). In this case spherical forms were detected through the orientation of intensity gradients. An important investigation was later conducted by Pla, Juste, and Ferri (1993), who focused on fruit detection for robotic harvesting and considered the fruit as a sphere illuminated by a beam of parallel rays. An approach combining shape analysis and colour analysis was presented by Plebe and Grasso (2001) who used stereo cameras placed on two telescopic arms to localize oranges, using a modified HSV (hue saturation value) space to enhance the contrast between the background and the oranges.

In the present study we focused on the development of an algorithm for localizing spherical fruits that have a smooth surface, such as apples, using only shape analysis and in particular convexity. More specifically, we propose to use intensity models to identify edges that bound spherical bodies within a predefined size range. Convexity is a very powerful but complex property of three-dimensional objects, and its study and use have not yet been fully investigated. For instance, under typical circumstances, the human eye can extract objects and estimate their sizes even when their edges are not seen, using only convexity properties of these objects.

The importance of convexity detection has been stressed since the earliest works in image analysis. However, most of these works discuss convexity of plane objects (plane spots, their borders, contours and silhouettes), convex hulls of two-dimensional (2D) and three-dimensional (3D) objects and various issues related to these themes (see, for example, Castelán and Hancock (2006), Ronse (1989) and the series of Rosenfeld yearly reviews published from 1988 until 2000, e.g. Rosenfeld (2000)). According to Bottino and Laurentini (2008), for reconstructing 3D shapes "*active 3D scanning is currently a leading technology. However, 3D scanners are expensive and affected by several limitations. In a number of practical applications … traditional computer vision techniques based on 2D images captured by inexpensive cameras are preferable or required*", so that detecting three-dimensional convex objects in two-dimensional images is a problem that is relevant to many applications.

In order to proceed within this "convexity framework", we must first answer the following basic question: are the intensity or luminance profiles of three-dimensional convex bodies necessarily convex? To answer this question, let us consider the simplest situation of an ideal sphere illuminated by a distant point source of light. Figure 1 shows schematically the perceived sphere when the light source is moved along a circle in the plane perpendicular to the drawing and going through the centre of the sphere and the point P, at 45° increments. For clarity, only situations relevant to the present study (i.e. light source in front and above sphere) are shown in Fig. 1. Sketched profiles of the corresponding intensity or luminance along a segment AB are also shown. We see that even under these simple lighting conditions, the intensity or luminance profiles may be non-convex. Thus, the commonly used assumption that smooth convex regions of three-dimensional bodies always or "usually" correspond to regions of convex intensity or luminance functions (e.g. Castelán & Hancock, 2006; Jimenez, Ceres, & Pons, 2000; Whittaker et al., 1987) is not always correct. In many applications, such as the one described in the present study, assuming that convex 3D bodies can be detected by detecting convex intensity profiles yields unacceptable results. Based on this observation, the first part of this study was devoted to developing and validating a simple model describing the intensity profiles of spherical or nearly spherical bodies illuminated by a distant light source.