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Research Paper

Co-robotic intra-row weed control system

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The automation of intra-row weed control in row crop production systems is very challenging. This work describes the development and in-field assessment of an automatic intra-row, hoe-based weeding co-robot system with real-time pneumatic hoe actuation based on an accurate odometry sensing technique. The US National Science Foundation has identified a need for robots (called co-robots) that serve as co-workers and work beside, or cooperatively with, people. These co-robots have a symbiotic relationship with a human partner, where, as a team, they combine their relative strengths to jointly perform a task. Such co-robots should be relatively inexpensive and easy to use. In this work, mechanical weed control was achieved by a co-robot actuator that automatically positioned a pair of miniature hoes into the intra-row zone between crop plants. The design was tested in a precision transplanted row crop and may also be suitable for direct seeded row crops. Co-robot cost was minimised by limiting the system to a single, simple odometry sensor. Co-robot hoe actuation was controlled using pre-programmed knowledge of the crop planting pattern and real-time odometry data as the control input for hoe positioning. Low-frequency drift in the odometry control points relative to the actual plant locations was corrected occasionally as needed in real-time by a human partner monitoring system performance. The co-robot was evaluated in an experimental trial conducted on the UC Davis campus farm. Assessment was based upon the follow-up hand hoeing required after automated intra-row weeding in comparison to the labour required to manually hoe a control plot. The mean person hours required for hand hoeing weeds in the control were 0.241 h for the 100 m^2 plot, while only 0.102 h 100 m^{-2} were required in follow-up labour to complete the weed removal in the plots weeded by the co-robot. This represents a 57.5% reduction in hand labour requirements for intra-row weed control and indicates that the co-robot could help reduce traditional hand hoeing labour requirements with mechanised weed control in intra-row areas between the crop plants.

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1. Introduction

In organic crop management the use of conventional pesticides is prohibited, placing a major challenge and priority on most organic farms for mechanical weed control (Walz, 2004). While economic non-complex equipment is available to control the inter-row weeds, intra-row weed control still requires costly hand weeding (Silvesind, Leblanc, Cloutier, Seguin, & Stewart, 2009). In many crops (e.g., onions) this added labour cost can be significant (Mojzis, 2002).

Agricultural workers who perform manual weeding are exposed to several musculoskeletal disorder (MSD) risk factors, particularly prolonged trunk flexion angles (AgSafe, 1992). For hand weeding of organic crops, the task frequently causes the individual to work in a stooped and uncomfortable posture for long periods, which may result in serious chronic health issues to workers, and substantial direct and indirect costs to growers. Depending on the intra-row weed density, Danish studies have shown that 50–350 h ha^{-1} were required for manual weeding in leek and bulb onion crops (Melander & Rasmussen, 2001). For organic production of broccoli and leaf lettuce in California, the average time required to hand hoe for weeds, and weed and thin was 53 h ha^{-1} and 40 h ha^{-1}, respectively (Tourte, Smith, Klonsky, & De Moura, 2004, 2009). The average cost of hand hoeing in these crops was \$628 (2009 US\$ ha^{-1}) and \$541 (2004 US\$ ha^{-1}), respectively.

Hand weeding (and thinning for lettuce) operations in organic production of these crops represents ~95% of their total weed control costs. Although chemical herbicides are registered for use in conventional vegetable crop production systems, the number available is limited and they are not completely effective (Fennimore, Tourte, Rachuy, Smith, & George, 2010). For example, in conventional broccoli and lettuce production systems, hand weeding costs represent about 50%–60% of weed control costs (Smith, Chaney, Klonsky, & De Moura, 2004; Tourte & Smith, 2010).

Current technology exists for effective control of weeds present between crops rows. For example, disc cultivators (Bowman, 1997; Mohler, 2001), brush weeders (Fogelberg & Kritz, 1999), rolling cultivators (Lampkin, 1990) and rolling harrows (Peruzzi, Ginanni, Raffaelli, & Di Ciolo, 2005). The critical need for development of weed control technology is for the removal of weeds between the crop plants along the row centreline, and this is still largely done by hand, adversely impacting production costs.

Currently, some commercial machines for intra-row weeding are available to farmers. Some examples are:

i) the finger weeder, which is capable of removing weeds in the seedline, but weeds need to be small (2nd true leaf or smaller) and the crop firmly rooted (typical price US\$860 row^{-1} and field capacity 1 ha h^{-1}) (Turner, 2000),
ii) the torsion weeder, which is capable of removing weeds in the seedline, but again the weeds need to be small (2nd true leaf or smaller) and the crop firmly rooted (typical price US\$180 row^{-1} and field capacity 1 ha h^{-1}) (Bowman, 1997),
iii) the weed blower, which uses compressed air to control weeds by blowing them out of the crop row (typical price US\$2100 row^{-1} and field capacity 1 ha h^{-1}) (Lutkemeyer, 2000; Vale, 2003),
iv) flame weeding, which can be less costly than hand-weeding in some cases, but there is a high machine cost (typical price US\$4700 row^{-1} and low field capacity) (Ascard, 1998), and
v) current state-of-the-art intelligent systems (e.g., Robocrop) using digital cameras to view the crop and use computer-controlled hoes to remove weeds (typical price US\$17000 row^{-1} and speed limited to 3 km h^{-1}) (Dedousis, Godwin, O'Dogherty, Tillett, & Grundy, 2007).

Interested readers are referred to recent reviews on these systems by Cloutier, van der Weide, Peruzzi, and LeBlanc (2007), Fennimore, Hanson, et al. (2014), and Hofstee and Nieuwenhuizen (2014). Ascard, Hatcher, Melander, and Upadhyaya (2007) suggest that the constraints of cost, low capacity, low selectivity and time to perform all the necessary adjustments have made a number of recently developed weed control systems unattractive.

Fennimore, Smith, Tourte, LeStrange, and Rachuy (2014) conducted an on-farm evaluation of the Robocrop (Tillett, Hague, Grundy, & Dedousis, 2008), a state-of-the-art intelligent commercial (Garford, 2014) intra-row cultivator based on a machine vision sensor and a rotating disc hoe for intra-row weed control in four vegetable crops (bok choy, celery, lettuce, and radicchio) in California. Fennimore, Hanson, et al. (2014); Fennimore, Smith, et al. (2014) observed that, in general, the Robocrop cultivator removed more intra-row weeds than a conventional commercial "close" inter-row cultivator and thus reduced hand-weeding times more than the standard inter-row cultivator, although the hand weeding time reduction was sometimes small in magnitude. They also observed, however, that the Robocrop cultivator did not have the level of precision necessary to weed or thin direct-seeded lettuce (5–7 cm intra-row crop plant spacing) and consequently reduced crop stands, lowered crop yields, and resulted in lower net economic returns (including equipment use costs) when compared to conventionally hand weeded and thinned lettuce production. In a transplanted vegetable crop (~25 cm intra-row crop plant spacing), the net economic return for the Robocrop cultivator was similar to the net return in the hand weeded crop.

Co-robotic systems are robotic systems that work in close cooperation with humans (NSF, 2011). Co-robots take advantage of automated mechanical, electronic, and computer technologies to establish a symbiotic relationship with their human partners, each leveraging their relative strengths in task planning and execution. These co-robotic systems are able to aid their human counterparts in dangerous, repetitive, or time-consuming tasks. To be commercially successful, co-robots must be relatively inexpensive and easy to use. In the case of hand weeding, the co-robot can take on the drudgery of repetitive hoe movement in and around each crop plant along the row, while the human partner has a superior visual sensing system and can initially synchronise the co-robot hoe position relative to the crop and then occasionally (<0.1 Hz) adjust co-robot actuator control setpoints in real-time to ensure accurate and consistent intra-row weed hoe positioning across the entire field. Because the complex crop