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A string twining robot for high trellis hop production

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ABSTRACT

The hop plant is usually trained to grow on strings in commercial production. String twining is a labor intensive task in high trellis hop fields, and there is a high demand from industry to have the operation mechanized. In this study, an innovative string twining robot, comprising end-effectors for knot tying, string feeding, and trellis wire capturing was designed to perform this task autonomously. A laboratory-scale, proof of concept prototype, was fabricated to validate the performance and effectiveness of this robotic device and associated control algorithms. Functionality assessment tests verified that the string feeding end-effector could feed 6 m length of string with acceptable variation. The trellis wire capturing end-effector could functionally achieve the required procedure for continuous twining. The comprehensive twining test proved that the integrated twining robot took approximately 11.2 s to coordinate all three end-effectors to complete one string twining cycle with a moving forward speed of the mobile platform at 0.19 m s^{-1}. At this speed, the developed prototype robot achieved 97% of successful rate. The laboratory test results indicated that the developed prototype robot has the potential to be implemented for high trellis hop twining task.

1. Introduction

The State of Washington is the major hop production state in the United States, with about 9500 ha of hops planted in 2011 accounting for 79% US production (USDA-NASS, 2011). Almost all of the hops in Washington are grown in 5.5 m high trellis systems (WSDLI, 2002). One essential operation in high trellis hop production is string twining on trellis wires. The twining process consists of two major tasks of tying one end of a string on an overhead trellis wire, and staking the other end into the ground. In the State of Washington, twining operation begins in April and it requires tying approximately 4500 strings per hectare (personal communication with growers in wash). Conventionally, growers in the region fasten strings on trellis wires using clove hitch knots. Fig. 1 shows a typical high trellis hop field after strings has been twined. Currently, string twining is performed manually by highly trained field workers. The aging and declining availability of workers creates a major challenge to hop production. Aimed to solve the aforementioned challenges, this research was to develop a robotic solution to tie clove hitch knots on trellis wires and replace the need for human workers.

Mechanical knotting devices have been widely studied for different purposes (Torres and Riehm, 2003; Thomas and Jenkins, 2003; Singhatat and Corporation, 2004). The knot tying process in hop twining is quite similar to that for tying the bales. However, knots in hop twining are placed on a very small size overhead wire using one string end, and the baler process using two string ends putting the knots on either square or round bale for the baler (Schoonheere et al., 2007). People have put efforts in the past to develop mechanical twining solutions. For example, Keller Swartwood Engineering, Inc. (2003) designed and fabricated a prototype of self-propel automated twining machine for attaching strings on overhead wires using hog rings. While, the hog rings could not fasten the string on the trellis wires, causing the string sliding on trellis wires under strong winds which commonly occur during the hop growing season. The moving of strings resulted in unacceptable wearing of string worn-out and the hop vines falling down on the ground. More recently, Gobor and Fröhlich (2010) and Gobor et al. (2012) in Germany developed a mechanical device capable of performing a fully automated twining operation to fasten metal wires on trellis wires for hop production. However, Washington growers prefer to use fiber string rather than the metal string. As all reported inventions could not meet the need of tying clove hitch knots required by growers, researchers at Washington State University (WSU) have worked closely with the hop industry to develop robotic solutions for tying clove hitch

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Fig. 1. An example of typical high trellis hop field after being twined in the State of Washington.

knot using fiber string, and successfully invented a couple designs of knot tying end-effecter capable of tying the required knots on trellis wires (He et al., 2012, 2013).

The work described in this paper builds upon this accomplishment toward the development a robotic string twining machine. The primary goal of this study was to develop complementary components to support the previous developed knot tying end-effector. To create a fully automated robotic string twining machine, the components developed included a string feeding end-effector and a trellis wire capturing end-effector. A series of equations were used to express the actions of the string feeding end-effector and the trellis wire capturing end-effector to provide the baseline information for their functionality tests. Finally, a series of laboratory test was conducted to evaluate the performance of the integrated robotic device, including string feeding, trellis wire capturing and knot tying devices.

2. Materials and methods

2.1. Knot tying procedures

The method of knot tying used in this study has reported in our previous study (He et al., 2013). Fig. 2 illustrates the step-by-step procedure of tying a clove hitch knot. In this process, one end of the string is brought to the starting point 1 by a string feeding end-effector, then a knot tying end-effector will grasp the string end to cross over a trellis wire twice to form two loops following a pre-defined trajectory from point 1 to point 2, then points 3 and 4, and finally pull the string end from point 4 to point 5 to complete a knot. The designated string material used here was a 4 mm diameter plant fiber string commonly used in Washington high trellis hop production.

2.2. Design of the string twining robot

The typical trellis used in Washington hop fields is constructed by trellis wires (on which strings are tied) and support wires (perpendicularly arranged to trellis wires to form a trellis network) commonly 5.5 m above the ground. Generally, it requires tying four strings on one section of trellis wire between two support wires to train the hop plants as illustrated in Fig. 3. In practice, the twining operation progresses in the direction of perpendicular to trellis wires. In order to achieve the proposed goal of performing the twining operation continuously, the twining robot was designed as illustrated in Fig. 4.

2.2.1. Design and control of string feeding end-effector

String with predetermined length should be placed to the designated position in a timely manner in each knot tying cycle. The detail of the string feeding end-effector is illustrated in Fig. 5. Three pneumatic cylinders (elements 4, 20, and 23), and an electric motor pair (element set 21) are used in the end-effector.

Fig. 6 shows the schematic of pneumatic actuating system of the string feeding end-effector. The actuating system used a three-way, two-position directional valves 33 (MME-31NES-D024, Clippard Instruments Laboratory, Cincinnati, OH) to extend pneumatic cylinder 4 to open pincher 3. This cylinder was retracted by an inside spring after the air pressure being released to close the pincher 3. One four-way, three-position directional control valve (elements 32.1–32.2, MME-41NES-D024, Clippard Instruments Laboratory, Cincinnati, OH) were used to swing arm 19 forward and backward through extending or retracting cylinder 20, and another valve of the same model to drive cylinder 23 to control cutter 24 performing cutting operations. Two two-way throttle check valves 35.1 and 35.2 (JFC-4K-P08, Clippard Instruments Laboratory, Cincinnati, OH) were used to adjust the speed of cylinder 20. A pair of electric motors 21 (DED216G, DeWalt, Baltimore, MD) were used to drive a pair of rollers to feed a string with predetermined length. The string length was measured by the time of the motor pair operating in a certain rotation speed controlled

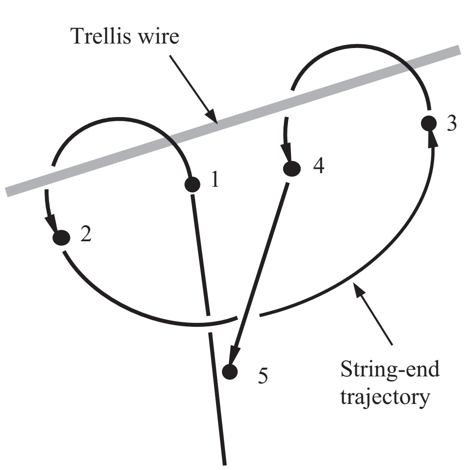

Fig. 2. An illustration of the clove hitch knot tying procedure.

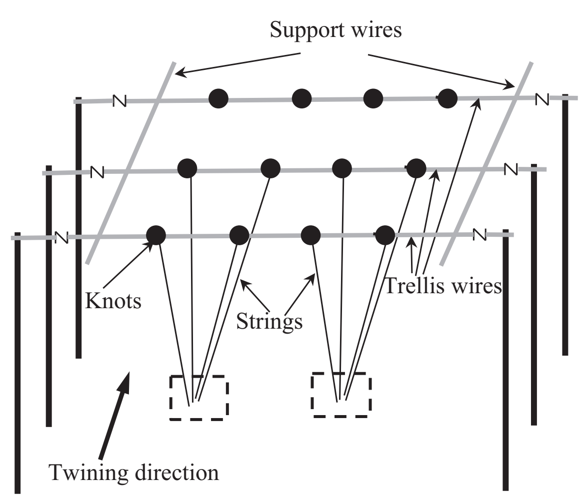

Fig. 3. An illustration of trellis system and string twining positions in typical Washington high trellis hop fields.