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IFAC-PapersOnLine 49-16 (2016) 061–065

Stability Analysis for Orchard Wearable Robotic System

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Abstract: This paper presents the preliminary stability study of a lifting-walking orchard wearable robot. The robot is operated by a single person, thus, stability is a major concern for the purpose of keeping the operator safe. The force-angle model is used in this paper for stability margin modeling of the wearable robot system. A possible control strategy is given based on the model. The relationship between footprint size, robot height, bending angle of the operator and the stability margin is discussed. The result indicates that it is possible to keep the robot system stable by the stability model.

Keywords: Orchard wearable robot, Stability margin, Force-angle model, Simulation

1. INTRODUCTION

The U.S. tree fruit industry is an important component of the nation's agricultural sector representing about 13% ($18 billion) of all crop production (Pollack and Perez, 2008). Most major orchard operations in tree fruit production, from pruning and thinning to harvesting, are heavily human labor dependent. In addition, almost all tasks require the use of ladders to reach the top of the canopy, which is highly strenuous and hazardous. Deaths and injuries from falls remain a major hazard for farmworkers. According to the Bureau of Labor Statistics, agricultural workers had a non-fatal, fall-related injury rate of 48.2 per 10,000 workers in 2011 (OSHA, 2014).

In addition, based on the statistics, only 30 percent of an apple picker's time is actually spent picking the fruit. During the remaining time the worker is climbing up and down the ladder, moving and resetting the ladder, or walking back and forth to dump the fruit into the bin (Good Fruit Grower, 2009).

As an alternative, the adoption of automated lift platforms for orchard tasks have been explored, but multiple people working together on one automated platform typically slows operations due to both difficulties in synchronizing processes and workers with different levels of productivity (Robinson and Sazo, 2013; Sazo et al., 2010; Duraj et al., 2010).

Therefore, development of a lifting wearable robot which can be operated by an individual could be a more efficient approach to assist people working in tree fruit orchards.

Exoskeleton robots are commonly used for helping people with disabilities (Kiguchi et al., 2003) or assisting humans, especially soldiers, with strenuous tasks like lifting or carrying heavy loads (Zoss et al., 2005, 2006). However, the exoskeleton type, lifting-walking wearable robot for improving productivity and safety of human workers during orchard operations has not been investigated.

Operator safety is the number one design consideration for a wearable robot. Furthermore, for a robot that can lift the operator to a high position, the possibility of the tiping over is a major concern. Therefore, stability is a primary design aspect that needs to be considered.

The force-angle model is widely used to judge the stability of a dynamic system (Papadopoulos et.al, 1996, 2000), which facilitates programming and calculation. Thus, this method was selected to measure the stability margin of the wearable robot along with MATLAB simulation. Based on the force-angle model and the numerical simulation, influences of key design parameters on the stability of the wearable robot system is discussed.

2. MODELING OF THE STABILITY MARGIN

In order to accomplish most tasks in an orchard, we assume the wearable robot can lift the operator to a maximum height of 1.2 m. A specific dimension of the base is needed to prevent the robot system from tipping over. Fig. 1 shows one possible structure of the robot.

2.1 Without external force

In Fig. 1 and Fig. 2, point G is the center of mass of the whole system. The rectangle $P_1P_2P_3P_4$ represents the footprint plane of the system. Let vector f_G represent the gravity, then G′ is the projection of G on the plane.

10.1016/j.ifacol.2016.10.012

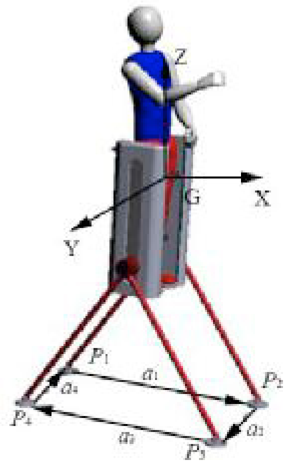

Fig. 1. A lifting-walking wearable robot.

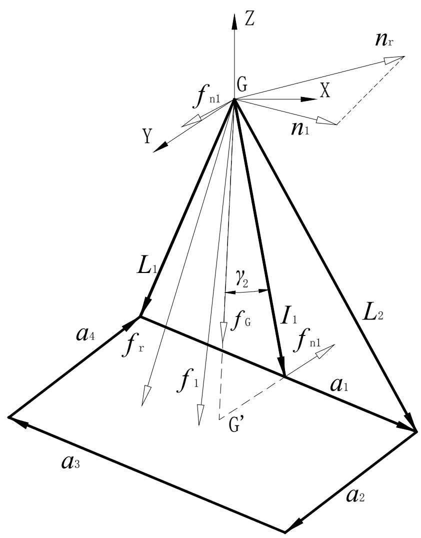

Fig. 2. Schematic of the system for stability model.

If no external force is applied on the system, then gravity and reaction force of the surface are the only forces acting on it.

When the point G′ falls outside the footprint, the balance of the system will be lost. Since the system may tip over around the four edges of the footprint, the angle γ_i {i=1, 2, 3, 4} should always be positive in order to prevent the tipover of the system (Papadopoulos et.al, 1996, 2000; Wang et.al, 2013).

As shown in Fig. 2, the vectors a_i can be written as

$$\begin{cases} a_i = L_{i+1} - L_i & i = \{1,2,3\} \\ a_4 = L_1 - L_4 \end{cases} \tag{1}$$

The vector I_i normal to a_i that pass through the point G are described as

$$I_i = (1 - \hat{a}_i\hat{a}_i^T)L_{i+1} \tag{2}$$

where, $\hat{a}_i = a_i/\|a_i\|$.

Then the angle γ_i are given by

$$\begin{cases} \gamma_i = \sigma_i \cos^{-1}(\hat{f}_G \cdot \hat{I}_i) \\ \sigma_i = \begin{cases} +1 & (\hat{f}_G \times \hat{I}_i) \cdot \hat{a}_i > 0 \\ -1 & \text{otherwise} \end{cases} \end{cases} \quad i = \{1,2,3,4\} \tag{3}$$

where, $\hat{I}_i = I_i/\|I_i\|$, $\hat{f}_G = f_G/\|f_G\|$.

The stability margin can be defined as

$$\alpha = \min(\gamma_i) \cdot \left\|f_{\text{grav}}\right\| \quad i = \{1,2,3,4\} \tag{4}$$

where, f_{grav} is the gravity vector of the system.

A positive α indicates that the system is stable. However, if α is negative, the system will tip over, which happens when any angle of γ_i is negative. As shown in Fig. 2, raising the point G decreases the minimum γ_i and thus decreases the stability of the system. The introduction of $\left\|f_{\text{grav}}\right\|$ in the equation makes the stability margin α sensitive to the weight of the system.

2.2 With external forces

During the working period, the system may be subjected to external forces from the tools, the trees or even the wind. If the system is moving, an inertial force will act on it. External forces, the inertial force and the gravity can always be reduced to one net force f_r and a net moment n_r applied at the point G.

The components of f_r and n_r causing the tip over of the system are be given by

$$f_i = (1 - \hat{a}_i\hat{a}_i^T)f_r \tag{5}$$

$$n_i = (\hat{a}_i\hat{a}_i^T)n_r \tag{6}$$

The equivalent force of n_i acting on the point G is given by

$$f_{ni} = \frac{\hat{I}_i \times n_i}{\|I_i\|} \tag{7}$$

Then the new net force is

$$f_i^* = f_i + f_{ni} = (1 - \hat{a}_i\hat{a}_i^T)f_r + \frac{\hat{I}_i \times \left((\hat{a}_i\hat{a}_i^T)n_r\right)}{\|I_i\|} \tag{8}$$

Thus, Eq. (3) is rewritten as

$$\begin{cases} \gamma_i = \sigma_i \cos^{-1}(\hat{f}_i^* \cdot \hat{I}_i) \\ \sigma_i = \begin{cases} +1 & (\hat{f}_i^* \times \hat{I}_i) \cdot \hat{a}_i > 0 \\ -1 & \text{otherwise} \end{cases} \end{cases} \quad i = \{1,2,3,4\} \tag{9}$$

where, $\hat{f}_i^* = f_i^*/\|f_i^*\|$.

Therefore, the stability margin can be rewritten as

$$\alpha = \min(\gamma_i) \cdot \|f_r\| \quad i = \{1,2,3,4\} \tag{10}$$

2.3 Normalization

Normalizing the stability margin α yields

$$\hat{\alpha}_i = \alpha_i/\alpha_{\text{nom}} \tag{11}$$

where α_{nom} is the nominal value of the stability margin for the system when the operator is standing without any tools in hand and the wearable robot is on a planar surface in the lowest positon where magnitude a_i= 0.5 m.

3. CONTROL STRATEGY

The footprint size has a large effect on stability. The larger the footprint the more stable the system, but too big will make walking difficult. A sufficiently large footprint must be chosen