Design and Compliance Control of a Robotic Gripper for Orange Harvesting

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***Abstract*—The existing manual orange harvesting needs to be automated to reduce high labor cost and minimize perishing of fresh fruit due to manual harvesting . In this paper, a preliminary design of a robotic gripper for orange harvesting and its compliance control is presented. The main focus is to have a low cost and lightweight design with a soft touch, actuated by a lead screw based mechanism. During grasping and detaching of fresh fruit, robotic gripper is in direct physical contact with the fruit. Thus, gripper need to behave like a complaint system to generate adequate force for picking of orange and avoid bruising of fruits and other parts of plant. To incorporate compliance control, integral sliding mode control is employed which emulate the behavior of an ideal mass-spring-damper system. The effectiveness of the dynamic model-free controller is validated through simulation.**

***Index Terms*—Robotic Gripper Harvester, Integral Sliding Mode Control, Model Reference Compliance Control, Mass Spring Damper System**

I. Introduction

Conventional harvesting of seasonal fresh fruits is labor intensive and somehow challenging during harsh weather. Such traditional fruit harvesting is expensive, time consuming and often risky for labors. In addition, time constraint is a major factor, as such fresh market fruits are perishable and therefore, provide a narrow window for harvesting. Moreover, fresh fruit industry is facing huge pressure due to increasing labor cost and rising uncertainty of labor force shrinking in future [1], [2]. Consequently, automation of agriculture sector is becoming popular worldwide. However, several challenges e.g. unstructured environment, complicated tree structured, fruit size variation, proper graping control and insufficient speed of fruit harvesting as well as other numerous issues need to be addressed prior before these automation solutions are widely adopted [3], [4].

Agriculture is the backbone of Pakistan economy where huge amount of citrus fruits are produced annually [5]. There are approximately 30 different types of fruits that are produced. Citrus fruits are the largest among all varieties in the country. Total production of citrus fruits is approximately 2 million metric tons yearly in which about 90% comes from the Punjab province where proper irrigation system exists [6]. In 1991-1992 the production of citrus fruits was recorded 1.62 million tones. In addition, statistics show 2.1 and 2.4 million tons in 2008-2009 and 2014-2015, which shows approximately 30.8 percent rise in the productivity [2]. Pakistan is 13th largest country in production of citrus fruit [3]. Kinnow (Fig 1 depicts manual harvesting of Kinnow)is very popular and as it constitutes a larger position of exports to countries like USA and UAE [7]. In 2014-2015 total export of 393,000 tons was recorded which added 204 million rupees to the country economy [8]. However, huge reduction occurs in market supply during seasonal picking of fruits, due to lack of automation and sophisticated harvesting techniques.

Two state of the art mechanical harvesting approaches has been proposed in literature. (1) Bulk harvesting using shake and catch approach applying vibration to detach fruit from the tree. (2) Selective harvesting with robotic grippers, detail is available in [9]. In addition, significant research is available on robotic harvesting for selective fruits and vegetables [10]–[12]. A typical approach is to integrate machine vision based technique for localization and identification of fruit which are the prerequisites for harvesting fruit [13]. However, challenges such as fruit clustering and different lighting condition limit performance of vision based techniques.

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According to work reported in [14]–[16] robotic harvesters fall into four types: pulling, twisting, cutting and twisting/pulling. More detail of each type can be seen in [16].

In this paper, a preliminary 3D design of a robotic gripper for orange harvesting based on lead screw mechanism is discussed. In addition, integral sliding mode control employing a virtual mass spring damper system as a reference model to achieve a desired compliant behavior is presented. This approach of orange harvesting with low cost gripper having compliant control behavior and has a huge potential for fresh market orange harvesting. Additionally, it provides a theoretical basis to realize the compliance control of orange harvesting robot.

This paper is organized as follows. Section I presents introduction of robotic gripper harvesters, followed by section II which presents design of robotic gripper orange harvester. Section III is about compliance control of robotic harvester. Section IV presents simulation results and discussion.

Fig. 1. Manual harvesting of kinnow

II. DESIGN OF ROBOTIC GRIPPER HARVESTER

The key function of the robotic gripper fruit harvester is to approach the fruit, grasp and then detach the fruit from the tree. It is vital for gripper fruit harvester to emulate the human hand behavior and avoid damage to the detaching fruit, trees and adjacent fruits. Excessive force during fruit plucking and inappropriate stem detaching approaches can badly damage the fresh fruit. In addition, minimum number of the actuators can counteract high cost, weight and size of the gripper. Such systems with number of actuators less than degree of freedom is called under-actuated grippers. Moreover, the proposed design can be easily manufactured with both conventional machining processes and additive manufacturing techniques.

The proposed robotic gripper orange harvester (RGOH) is composed of three fingers. It is important to note that each finger consists of one link having dimension of 60mm $\times$ 12mm (length $\times$ width) and one revolute joint. In addition, soft polyurethane pads are attached to inner surface of each finger to counteract fruit bruising during harvesting. The contact surface of the finger is 40mm in length and 12 mm in width. Dimensions and CAD model of finger is shown in Fig 2.

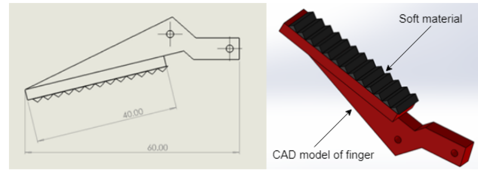

Fig. 2. Finger dimensions and CAD model

A DC Motor is employed with a lead screw mechanism to convert rotational motion into linear motion. The justification of using such mechanism includes the ease of availability of lead screw and the low cost manufacturing of other parts. The dimensions of lead screw are 22.5 mm (length) and 2 mm (diameter). Additionally, the cylindrical part is fused at the lower section of lead screw, to mount the motor shaft with it and ultimately to transfer motion of motor to the lead screw motion as shown in Fig 3.

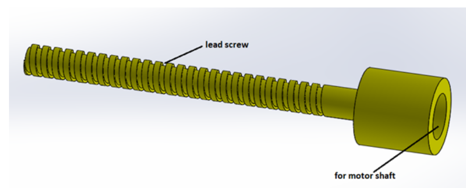

Fig. 3. Lead Screw

The nut type plate (known as drive plate) is designed for the robotic harvester to translate rotational motion of lead screw into the linear motion as shown in Fig 4.

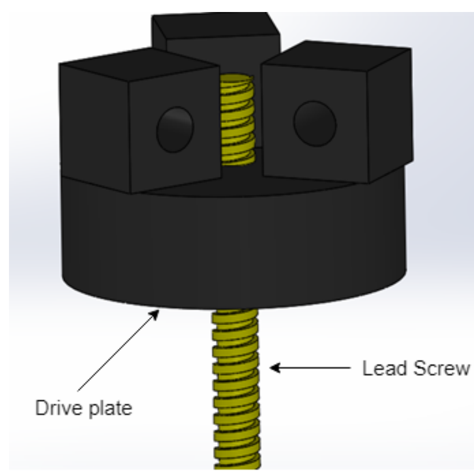

Fig. 4. CAD model of drive plate

The drive plate is fused to each finger through the link mechanism to move fingers with motor rotation. It is note worthy that fingers will grasp the orange with clockwise rotation of motor. In contrast, the fingers will release the orange when motor will rotate counterclockwise. The linkage mechanism is employed to transfer motion from drive plate to each fingers of the robotic gripper. The CAD model for fusing drive plate with finger through a link is shown in Fig 5.

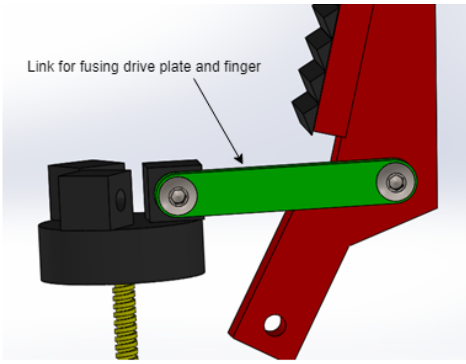

Fig. 5. Link

As mentioned earlier this proposed preliminary design of robotic gripper orange harvester consist of three fingers that are driven simultaneously by a single actuator located at the base of gripper. The conversion of rotational motion of motor into the linear motion and ultimately to drive the finger is govern by the lead screw mechanism. Complete CAD model design of proposed robotic gripper orange harvester is shown in Fig 6.

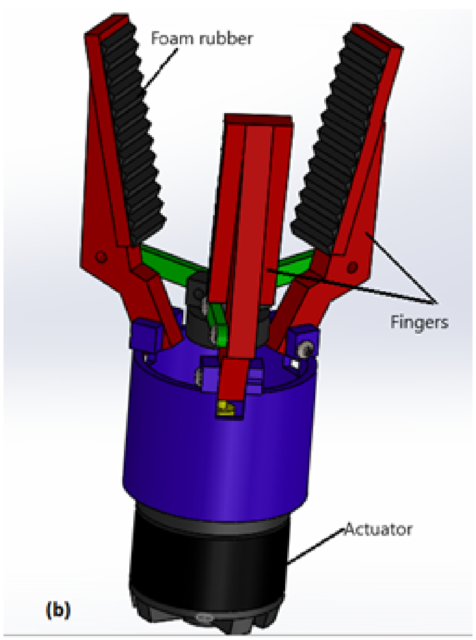

Fig. 6. CAD model of robotic gripper orange harvester

III. INTEGRAL SLIDING MODE CONTROL

Integral sliding mode control (ISMC) is a control technique which can counteract uncertainties, stiction and friction of the controlled system. ISMC approach is a robust and almost model free control technique [17] i.e., it doesn't necessarily need any precise knowledge of the dynamic model of the system unlike other control approaches such as feedback linearization. In addition, the idea of inherent internal reference model characteristics do not permit switching between states in contrast to hybrid control system; which permits ISMC for compliance control. Thus, the objective of employing ISMC is to achieve robust compliance control for robotic gripper orange harvester to minimize fresh fruit damage during picking. Moreover, numerous researcher highlighted that ISMC is superior than other controllers in trajectory tracking capability [18].

ISMC is an extended and advanced form of sophisticated control approach known as sliding mode control (SMC) which is a nonlinear robust control technique. For designing SMC approach two different phases are prerequisites to understand i.e, reaching phase and sliding mode phase [19], [20]. The SMC approach starts from reaching phase and take a bit time to reach sliding surface. In contrast, ISMC reach to sliding surface within no time i.e., there is no reaching phase. In addition, SMC approach has several limitations, for instance, chattering [21]. ISMC overcomes such challenges and follows the control command from the start and at the same time seamlessly deals with system uncertainties [22].

Consider the dynamic model of gripper harvester given in equation 1 based on general robot model [23],

$$\tau = J\ddot{\Theta} + \lambda(\Theta, \dot{\Theta}) \tag{1}$$

where $\tau \in \Re^{n\times 1}$, $J \in \Re^{n\times n}$, and $\lambda \in \Re^{n\times 1}$ represents input torque, moment of inertia, and friction and stiction terms, respectively.

Now, employing integral sliding mode control law [24] is given by equation (2). The ISMC variable s_i can be defined as in [18]

$$s_i = \dot{e}_r + K_s e_r + K_c \int_0^t e_r(\xi)d\xi - \dot{e}_r(0) - K_s e_r(0). \tag{2}$$

where K_s,and K_c represents proportional gain and derivative gain, respectively. The terms $\dot{e_r}(0)$ and $e_r(0)$ represents initial conditions. It is noteworthy, once the state trajectory reaches the sliding surface i.e. $(s_i = 0)$, system control depends on simple tunning of K_s and K_p; and the availability of initial conditions (t=0).

Now, integrating a PD controller with ISMC, the overall control law is

$$\tau = PD + \alpha \frac{s_i}{(||s_i|| + \delta)} \tag{3}$$

The scalar $\delta > 0$ (0.1) is used to shrink the effects of chattering [25]. The value of scalar $\alpha > 0$ (4000) should be large enough to make the systems robust.

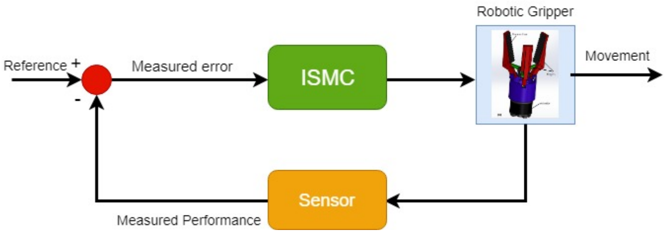

Fig. 7. Block diagram of ISMC based Gripper control

A. ISMC based active compliance control of RGOH

In this section a reference model for active compliance control based on ISMC is presented. The overall control structure of ISMC based compliance control for proposed robotic gripper orange harvester is depicted in Fig. 7. It is important to note that ISMC has inherent characteristics of internal model reference behavior which make it superior than other controllers. The sliding element s_i is altered based on the sensed torque using external torque sensors in joint.

$$s_i = \dot{e}_r + K_s e_r + K_c \int_0^t e_r(\xi) d\xi - \int_0^t s_p \tau_{ext} - \dot{e}_r(0) - K_s e_r(0) \tag{4}$$

where s_p and τ_{ext} are positive scalar and externally sensed torque measured with joint torque sensors. Taking 1st derivative of equation 4 and considering sliding mode i.e. $s_1 = 0$ and $\dot{s}_i = 0$, implies a second order dynamics for each robotic gripper harvester finger.

$$\ddot{e}_r + K_s \dot{e}_r + K_c e_r = s_p \tau_{ext} (s_i = 0) \tag{5}$$

where K_s and K_c are damping and stiffness coefficient, respectively. System realized to a second order compliant reference model for posited robotic orange gripper harvester. Fine tuning of K_s, K_c and s_p of reference model govern compliance behavior.

IV. Simulation Results

The ISMC based compliance control is implemented in Matlab/Simulink on the proposed gripper model. It is important to note that grasping and plucking of fresh fruits is very sensitive. A bit hard push, pull and twist during picking can badly damage the fruit. To counteract with fruit damage robotic gripper harvester should emulate the compliant behavior of mass spring damper system during harvesting process. Fig 8 (top) depicts a perfect position tracking control of robotic gripper orange harvester. The vertical axis shows position of finger (0 to 30 degree) and the horizontal axis shows time (0 to 11 seconds). The actuator provides a control input (Fig 8 bottom) torque (nm) to the fingers with the help of a lead screw mechanism which moves the fingers according to reference position. When step change occurs, control signal shoots up. Large spikes in control input are

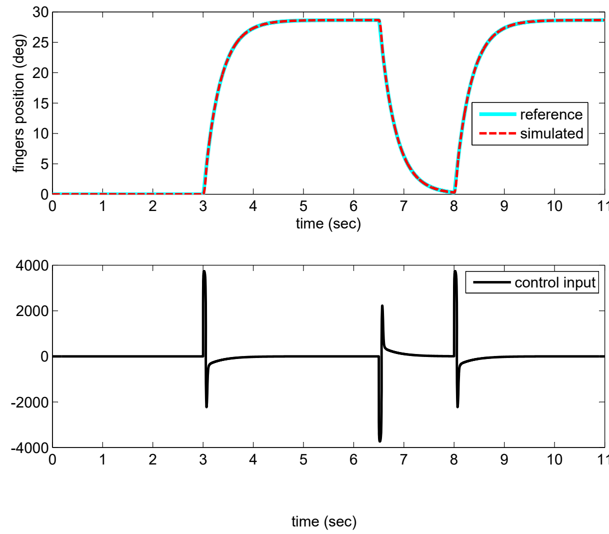

Fig. 8. Gripper fingers position

also due to higher α values (it doesn't pose any issue in simulation). However, the value of α will be limited in real system due to saturation limit of actuator. The fingers are tracking the desired position.

Fig 9 depicts the compliant behavior of robotic gripper harvester. Normally, the Griper provide necessary grasping force for plucking. However, once grasping force exceed the threshold of safe gasping force, compliance control comes in action and changes its behavior according to the circumstances (it adjust its position to compensate for the exceeding force). Various level of compliance behavior can be achieved by changing the values of damping coefficient (K_s) and stiffness coefficient (K_c) in the reference model as demonstrated in fig 9.

V. Conclusion

Robots are profoundly good within a controlled environment at doing same task again and again. On the other hand, it is highly challenging for robot to work in dynamic/changing environment. Although fruit harvesting through robot gripper is challenging. However, its timely need for the fresh fruit market to give energy and resources to develop robotic harvester. The key steps in the plucking process is orange prioritization, path planning, and detachment. Position and force control play vital role in fruit picking. In addition, compliance control can help to counteract fresh fruit bruising and other parts of tree while detaching fruit.

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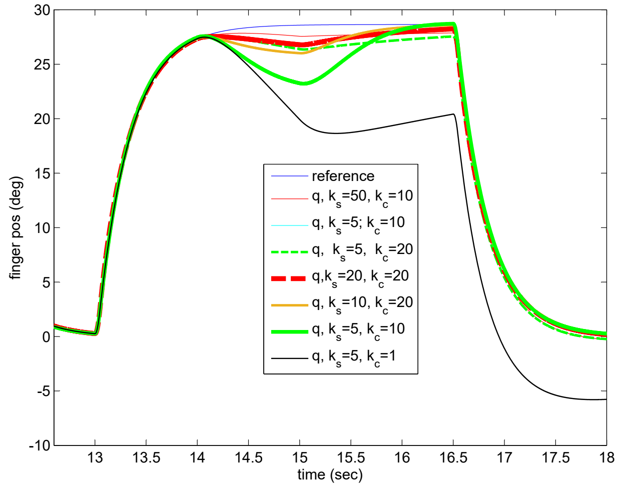

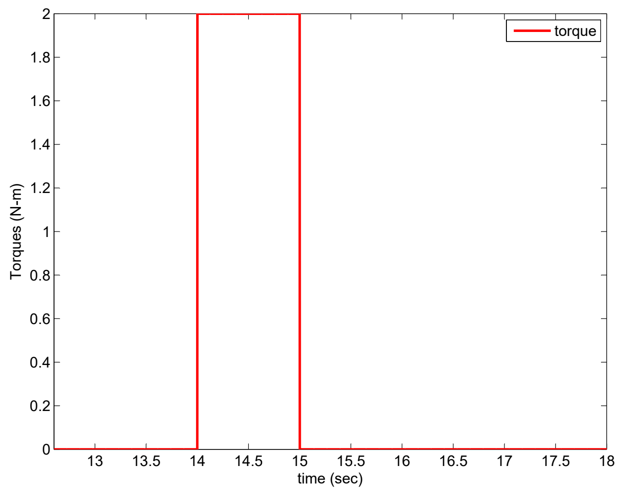

Fig. 9. Position of the figures for various k_s and k_c values (top), external torque (bottom).

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