Design of an Under-Actuated Mechanism for Collecting and Cutting Crop Samples in Precision Agriculture

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Abstract. Automating the processes of sampling and harvesting in precision agriculture is essential to expand the range of potential application scenarios. In this regard, this paper presents the design and development of an under-actuated device for grapevine harvesting and sampling. The tool is intended to be part of a set of tools from which a rover for precision agriculture can choose to perform various tasks. The tool presented in this paper is designed specifically for the gripper of a 7 d.o.f. robotic arm equipped by the rover Agri.Q, a service robot designed for agriculture. However, the design of the tool can be adapted to work with other robotic arm grippers. In this research, the gripper output contact forces and the required cut forces are experimentally measured to clearly define the design requirements of the tool. Then, the functional design of the system is described and a kinematic model of the mechanism is presented. Finally, the tool prototype is presented and tested with green peduncles ranging from 2 mm to 6 mm in diameter.

Keywords: SDG 12 · autonomous harvesting · under-actuated mechanism · service robot · precision agriculture.

1 Introduction

In traditional agriculture, the inherent challenges of resource management, labor efficiency, and environmental impact have long posed significant impediments to sustainable and optimized crop production. Precision agriculture channels technological advancements to address these challenges by incorporating data-driven methodologies [1]. Consequently, the integration of robotics stands out as a promising path. Robots equipped with advanced sensing, actuation, and decision-making capabilities hold the potential to reform farming practices, offering targeted and efficient interventions at a level of precision that is unattainable through traditional means [3].

Performing tasks such as harvesting, pruning, or any activity involving the precise cutting and collection of plant parts poses a significant challenge for robots due to the complex nature of the environment [8, 5]. In response to these challenges, the authors have proposed Agri.Q, a mobile robotic platform designed for precision agriculture in vineyards, featuring a robotic arm (Kinova Jaco 2) tailored for interacting with crops [2, 4]. Agri.Q has an eight wheels locomotion system, similar to one previously designed for the small-size robot Epi.q-Mod [6]. While the robotic arm incorporates a two-finger gripper suitable for general grasping tasks, the need for a specialized tool for cutting and collecting plant samples arises. To address this requirement without altering the robotic arm's end-effector, and to enhance flexibility and modularity, this study presents the design of an innovative under-actuated tool previously explored in [7]. This tool is specifically devised to cut and collect samples, utilizing a general-purpose robotic gripper for grasping and actuation of the tool.

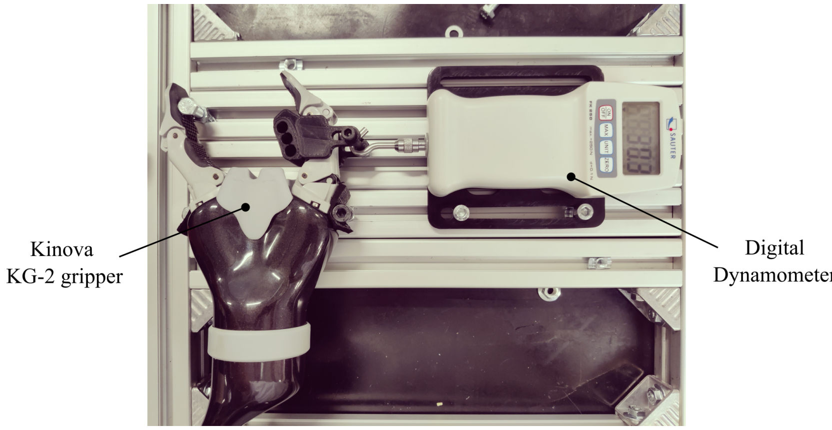
2 Design Requirements

The robotic arm gripper must autonomously grasp, hold, and control the tools needed. Moreover, the forces exerted by the gripper fingers should facilitate the tool actuation, initially securing a sample, then cutting its branch, and later storing the sample. Consequently, the designed mechanism should fit the robotic gripper and harness its grasping force to execute its tasks. Therefore, to achieve an optimal design, experimental data were collected for both the gripper grasping force and the required cutting force.

2.1 Gripping force evaluation

The design of the presented under-actuated tool for autonomous crop sampling envisions its easy adaptation on robotic grippers with different geometries and architectures. To develop an experimental case study, a tool has been designed and prototype has been built around the commercial Kinova Gen2 KG-2 model. This under-actuated two-finger gripper ensures the manipulation of cylindrical objects ranging from 55 mm to 100 mm in diameter. Even though different gripping modes are enabled by this gripper architecture, i.e. contact forces can be exchanged in different ways between the four phalanges and the target object, this work only considers a manipulation configuration where the proximal phalanges exert force on the grasping and cutting tool. This choice is based on the experimental characterization of the proximal and distal gripping forces of KG-2 as a function of its two degrees of freedom, which shows that the action of the proximal phalanges alone leads to the highest possible contact forces.

Fig. 1(a) shows the experimental layout used to measure the gripper contact force F_c on the proximal phalange, where the robotic end-effector is kept fixed, and a digital dynamometer evaluates the orthogonal contact force exchanged with the gripper over its whole range motion. The contact force, measured as the average value of ten runs, is 59 N in the maximum opening configuration and 29 N in the maximum closure configuration (Fig. 1(b)).



(a)

Test N°	F_c (max closure), N	F_c (min closure), N
1	29.9 ± 1.25	55.6 ± 1.25
2	30.1 ± 1.25	62.8 ± 1.25
3	30.3 ± 1.25	58.4 ± 1.25
4	29.3 ± 1.25	60.6 ± 1.25
5	28.9 ± 1.25	60.5 ± 1.25
6	29.2 ± 1.25	59.4 ± 1.25
7	30.0 ± 1.25	60.7 ± 1.25
8	27.5 ± 1.25	57.6 ± 1.25
9	28.4 ± 1.25	57.8 ± 1.25
10	29.4 ± 1.25	60.3 ± 1.25

(b)

Fig. 1: (a) Experimental setup to evaluate gripper contact force F_c on the proximal phalange in the maximum closure configuration. (b) Experimental results.

2.2 Experimental cutting forces

To evaluate the force required to cut branches of various diameters, a dedicated experimental setup was devised (Fig. 2(a)). A blade is fixed to a load cell mounted on a linear guide whose displacement is measured by a potentiometer. A second blade is placed at the end of the linear guide stroke. Several grapevine branches with diameter ϕ ranging from 1.5 mm up to 5 mm and different dryness were tested. For each test, a branch was held above the fixed blade, while the moving blade was pushed down until the branch was cut. Both the cutting force and the blade displacement readings were measured.

Figure 2(b) illustrates the filtered experimental data. Each curve depicts the initial contact of the moving blade with the branch (indicated by the onset of force increase) and the moment when the branch is successfully cut (marked by a sudden force drop). Typically, larger branch diameters ϕ correspond to increased cutting forces. However, branch dryness also influences the outcomes.

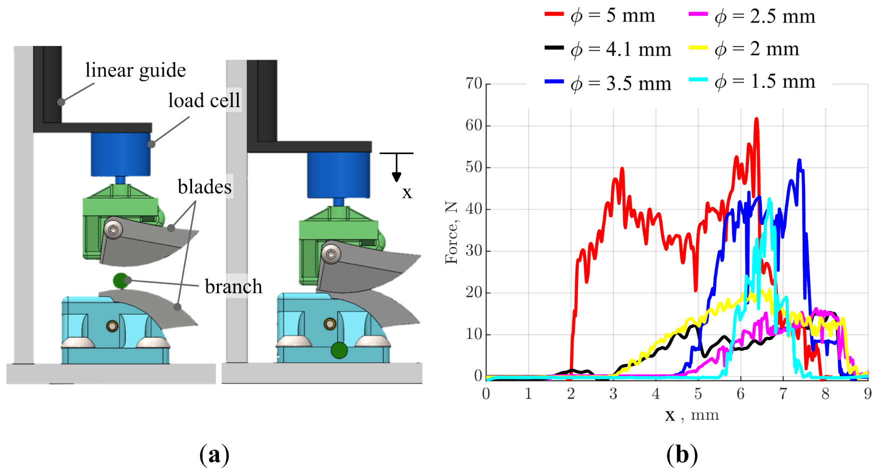


Fig. 2: (a) Experimental setup to evaluate branches cutting force. (b) Force required to cut branches of various diameters

Nevertheless, the primary parameter essential for the design of the cutting tool is the maximum required force, which is 60.6 N.

3 Crop sampling tool design

The under-actuated tool for autonomous crop sampling can be seen as a mechanical system in between the robotic gripper and the target crop. Thus, the gripper specifications and the cutting forces previously discussed constitute a set of requirements for the design procedure. Fig. 3 depicts the functional architecture of the tool, namely an under-actuated linkage with four links and two compression springs acting, respectively, between links 1 and 2 and between links 3 and 4. The combined action of these springs and a mechanical end stop (cursor in E) maintains the tool wide open when not actuated, as described by Fig. 3 (a). For clarity purposes, link 1 is represented as fixed, as well as the two hinge joints in D and B. In this fashion, the input force F_{in} exerted by the robotic gripper is entirely applied in A. Furthermore, C and F are the two points at which the blades cut the branch (Fig. 3 (b) and (c)).
It should be underlined that, in the actual device, none of the links of the mechanism is fixed to the distal link of the robotic arm. Link 1 and Link 2 have geometrical interfaces that match the geometry of the gripper fingers. One finger applies F_{in} to Link 2, as depicted in Fig. 4, and the other applies the same F_{in} to Link 1, symmetrically with respect to the X axis. Nevertheless, Link 1 is considered as fixed to simplify the quasi-static modelling of the mechanism (i.e., F_{in} applied to Link 1 is modelled as a reaction force).

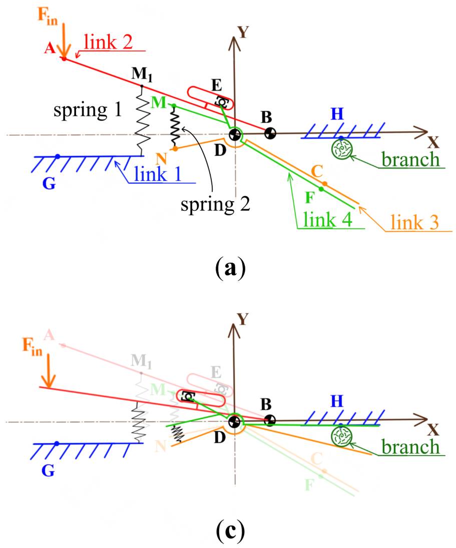


Fig. 3: Functional architecture of the under-actuated tool for autonomous crop sampling. **(a)** Rest configuration. **(b)** Grasping configuration (links 3 and 1). **(c)** Branch cutting (links 1 and 4) and subsequent holding (links 1 and 4). **(d)** Branch release.

3.1 Kinematic model

Fig. 4 shows a simplified representation of the crop sampling tool (link 3 devoted to branch grasping is not reported) and the geometric parameters influencing system performance. As main design specifications, the tool must guarantee the proper cutting of a peduncle with a maximum diameter of 6 mm with the reach of a maximum cutting force F_T= 60 N (Fig. 2) with an input force F_{in}= 30 N, that is the minimum orthogonal force exerted by the gripper in correspondence of the proximal phalange, as discussed above.

The tool performance can be evaluated in terms of both output blade rotation and cutting forces. If, on one hand, a higher output blade rotation allows the sampling of crops with a higher peduncle diameter, it also leads to lower values of output cutting forces. To this aim, the linkage gain parameter can be defined as follows:

$$G_F = \frac{F_T}{F_{in}} \tag{1}$$

Hence, the final set of geometric parameters, which allows a maximum angle $\beta \approx 20$ deg, a total encumbrance along $\hat{x}$ axis of 130 mm and a force gain factor $G_F \approx 2.5$, is reported in Table 1.

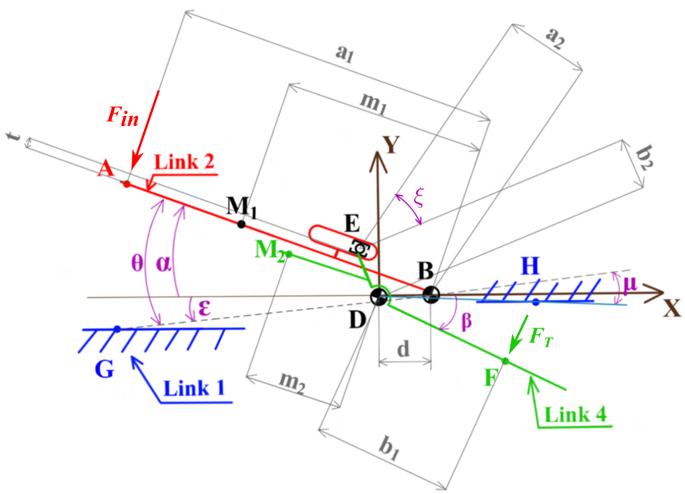


Fig. 4: Sampling tool geometric parameters.

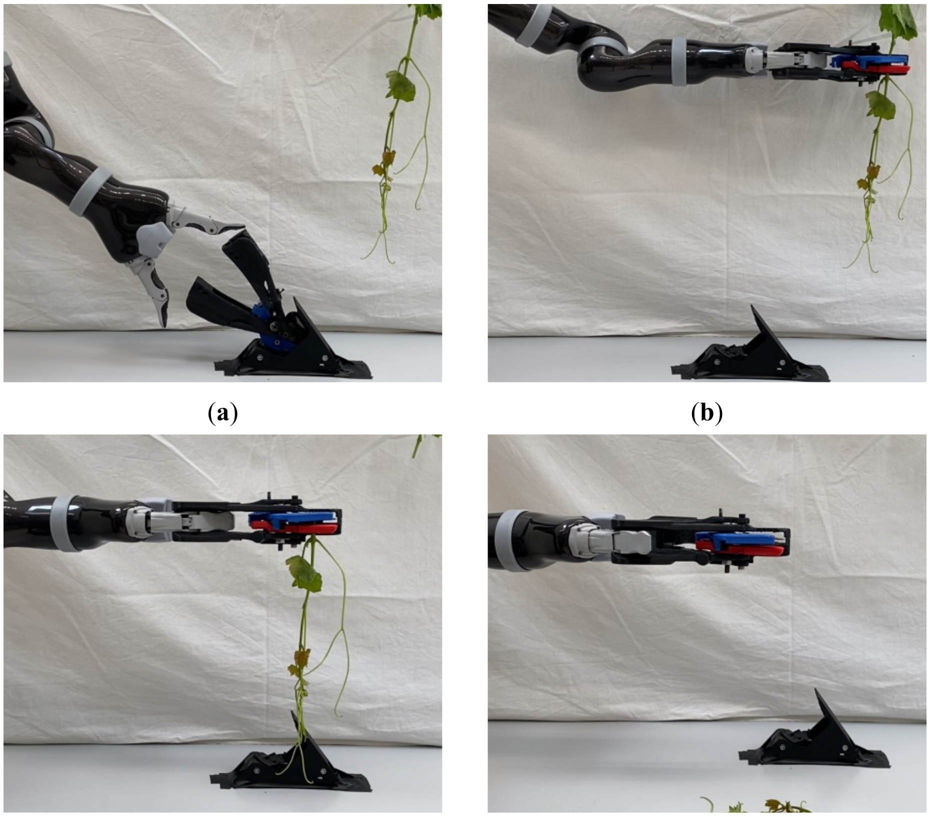
Table 1: Crop sampling tool final set of parameters.

Name	Value
a_1	130 mm
a_2	28 mm
b_1	25 mm
b_2	21 mm
d	15 mm
t	5 mm
$m_1 = m_2$	35 mm
K_1	0.58 N/mm
K_2	0.68 N/mm

3.2 Executive design and prototyping

To test the functionality of the mechanism, a prototype was built mainly in additive manufacturing based on the previous considerations. Links 1 and 2 were shaped to accommodate the 2-finger gripper and facilitate an autonomous and secure grasping of the tool. By redesigning the geometry of these two links, it is possible to adapt the device to other two-finger grippers. The two blades have been slightly modified starting from commercial blades for manual pruning. A high friction layer was added to link 3 to securely hold branches. All springs present a preload regulation system to tune the under-actuated mechanism behavior.

The developed tool and its entire application process were experimentally validated. In Fig. 5, the steps of operations for a sampling task during the ex-



(a) (b) (c) (d)

Fig. 5: Operation sequence for the grasping and cutting of a sample: **(a)** tool grasping, **(b)** peduncle grasped, **(c)** peduncle cut, **(d)** sample released.

perimental trials are depicted. The functionality of the tool was validated with green peduncles ranging from 2 mm to 6 mm in diameter.

The test followed a predetermined automated procedure, leveraging prior knowledge of the peduncle's pose concerning the robotic arm. In the structured and controlled laboratory environment, the robot equipped with the tool performed a grapevine sample collection with a success rate of 100%.

4 Conclusions

This paper details the design, testing, and experimental validation of a crop sampling tool aimed at collaborative robotic arms, specifically those with two fingers grippers, for automated grapevine harvesting and sampling. This tool is conceived as part of a toolset from which a rover for precision agriculture can automatically choose. In particular, this research is part of the project Agri.Q that mounts a collaborative 7 d.o.f. robotic arm, the Kinova Jaco2. Leveraging the tool's under-actuated mechanism and passive interface compatible with commercial two-finger grippers, the device exploits a single input for both grasping and cutting procedures. Experimental tests were conducted to evaluate gripper grasping forces and required cutting forces and to drive the tool design. Secondly, the under-actuated mechanism is described and a kinematic model of the device is derived. Based on the required cutting forces and available gripper forces, the force gain of the device was selected as 2.5. The paper concludes with the executive design, prototype development, and successful experimental validation of the grasping and cutting tool. Although the experimental trials do not take into account all the uncertainties that would affect the real implementation of the concept in an agricultural environment, this preliminary study has demonstrated that the concept of interchangeable tools that can be autonomously grasped and used by the robot arm is worthy of further investigation. As further developments, sensors and control algorithms will be added to the system to measure the relative pose of the peduncle to be cut with respect to the robotic arm. When the process will be fully automated, the last stage will be to assess the effectiveness of the tool in terms of accuracy, repeatability, efficiency, and resolution, which are strictly dependent on the entire system performance.

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