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Design and Prototyping of an Interchangeable and Underactuated Tool for Automatic Harvesting

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Abstract: In the field of precision agriculture, the automation of sampling and harvesting operations plays a central role to expand the possible application scenarios. Within this context, this work presents the design and prototyping of a novel underactuated tool for the harvesting of autonomous grapevines. The device is conceived to be one of several tools that could be automatically grasped by a robotic manipulator. As a use case, the presented tool is customized for the gripper of the robotic arm mounted on the rover Agri.Q, a service robot conceived for agriculture automation, but it can be easily adapted to other robotic arm grippers. In this work, first, the requirements for such a device are defined, then the functional design is presented, and a dimensionless analysis is performed to guide the dimensioning of the device. Later, the executive design is carried out, while the results of a preliminary experimental validation test are illustrated at the end of the paper.

Keywords: precision agriculture; SDG 12; autonomous harvesting; interchangeable tool; modular design; underactuated mechanism; service robot

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1. Introduction

In recent decades, precision agriculture (PA) has been established as a potential solution to the rapid increase in the food demand [1–3], also reducing costs and the waste of resources [4,5]. For the potential improvement in farm activities with a constant attention to responsible production, PA methods are consistent with the Sustainable Development Goals (SDGs), adopted by all United Nations Member States in 2015 as part of the 2030 Agenda for Sustainable Development [6]. In detail, the 12th SDG is entirely focused on the sustainable and improved production patterns, since the global population is expected to grow to up to 9.7 billion in 2050, according to the latest projections [7]. Thus, even though farm production has significantly increased thanks to automation [8], there are still several areas where intelligent machines can help human beings, relieving them from repetitive and time-consuming activities [9]. Since PA is mainly a data-driven approach for traditional farming activities [10,11], several solutions regarding sensing and monitoring were proposed in recent decades [12,13], to collect a large range of data coming from the crop and soil to provide information such as the state of the ripeness [14–16], the nutrient content [17–19] and the crop mass and size [20,21]. Considerable attention was nonetheless given to mobile robotic systems that can navigate and operate without a human presence, categorized as AGVs (unmanned aerial vehicles) and UGVs (unmanned ground vehicles) depending on their locomotion system, where UGVs have the significant advantage of filling the gap between mere sensing and monitoring and enabling the ability to interact with the environment, thus allowing the execution of typical and classical farm activities, e.g., seeding, weeding, trimming spraying and harvesting. In Figure 1, some examples of UGVs designed for pruning, spraying and harvesting are depicted [22–28].

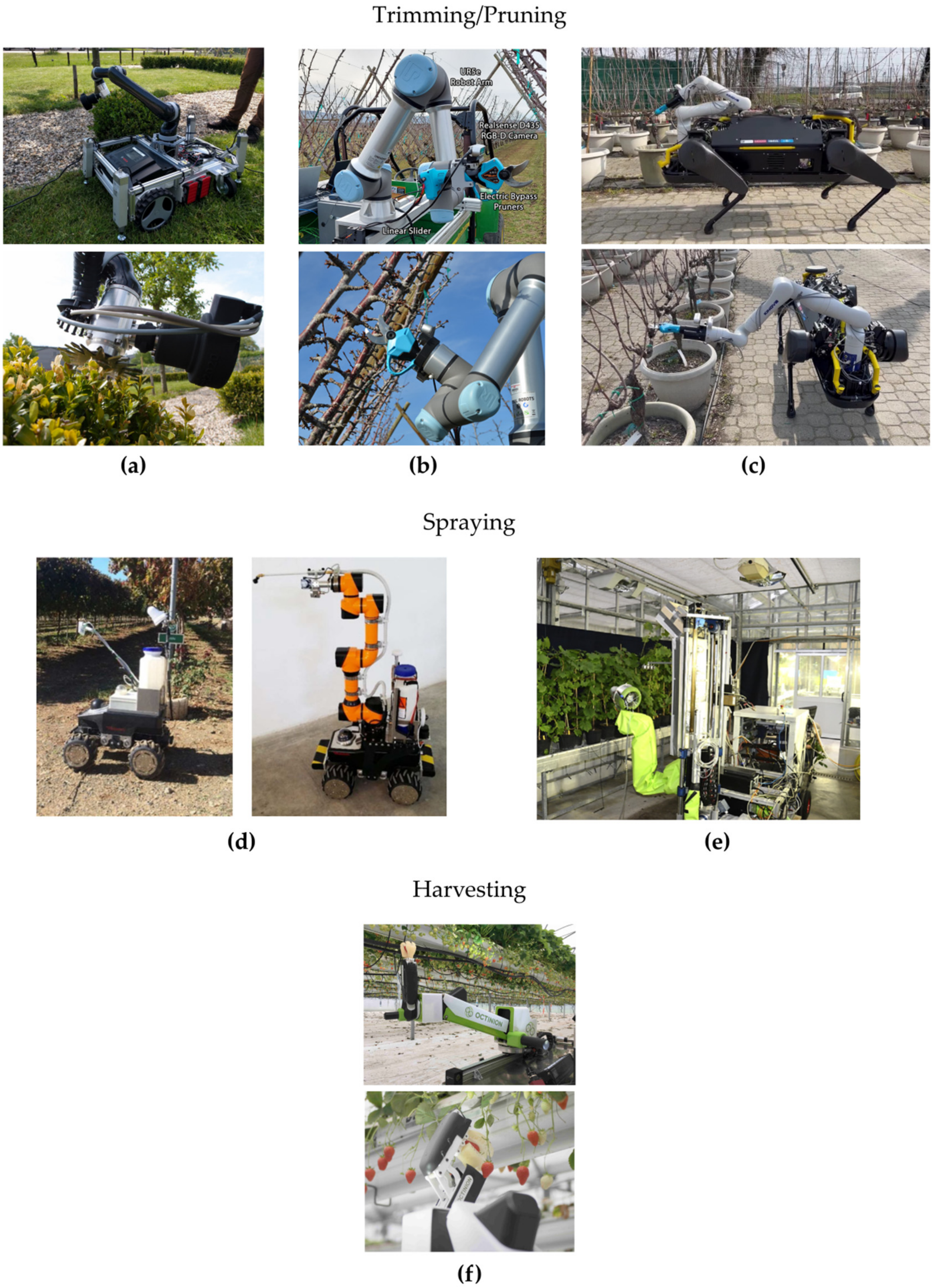


Figure 1. Brief overview of UGV systems for precision agriculture (PA). (**a**) TrimBot2020 for bush trimming [22], (**b**) robotic system for sweet cherry tree pruning [23], (**c**) vinum project for grape pruning, reprinted with permission from Refs. [24,25], (**d**) AgriRobot and SAVSAR for autonomous vineyard spraying [26], (**e**) crops mobile robot for selective spraying of grapevines, reprinted with permission from Ref. [27]. 2016, Elsevier. (**f**) autonomous robot for strawberry harvesting. © 2018 International Federation of Automatic Control. Reproduced with permission from [28].

The common approach for the development of the aforementioned systems is the integration of a mobile base with a serial robotic manipulator [22–26,29], while for [27,28] a custom manipulator was designed. It is quite straightforward that, depending on the specific application and culture, the arm is provided with a tool for the required task of replacing the traditional arm gripper, thus opening the doors to plenty of research on custom systems, both deformable (so-called soft grippers) [30] or rigid ones [31], that can be classified according to their type of actuation, type of mechanism, mode and method of gripping. Addressing harvesting tasks, in [32], a general-purpose soft gripper for fruit harvesting and handling is presented, which can be manufactured with the use of a 3D FDM (fused deposition modelling) printer and PDMS (polydimethylsiloxane), known for its elasticity and property of curing at room temperature. In [33], a rigid-link customized gripper is mounted on a Kinova commercial robotic arm for grapevine harvesting, addressing the need for coupled cutting and gripping operations by means of a scissor-like architecture, even though no more insights about the tool design are provided. In [34], the same problem is tackled with the development of a custom tool that is provided with a sliding single blade instead of a scissor-like architecture. In [35], a scissor-like cutting tool with a gear wheel drive and coupled with a double parallelogram gripper for peduncle picking is presented and tested on grapevines. To this aim, the mechanism geometry is given by a commercial scissor and the gear wheel drive is dimensioned by an experimental evaluation of the required cutting force. In [36], a second-class lever architecture clipper for fruit picking is presented, where the presence of an intermediate plate allows for the coupled motions of picking and cutting. It is worth noticing that the tool is designed to be mounted on the standard gripper of the Fetch mobile manipulator [37], even though the authors do not indicate whether the mounting procedure can be automatized, or it must be performed by a human being.

The state-of-the-art of research on the tools for precision agriculture shows how a large number of solutions are aimed at substituting the standard commercial gripper with a custom one, that eventually integrates the cameras or other sensing components. Even though the custom-tool paradigm is reasonable when addressing a specific field task, the adaptability and flexibility of the system may be affected or even taken out. Moreover, even though some contributions aim at designing a general-purpose tool for coupled picking and cutting, the design methods are seldom illustrated [33,34] or significantly constrained by commercial solutions [35].

To this aim, the paper presents the design and prototyping of a novel underactuated and interchangeable tool for robotic grippers for the autonomous harvesting of grapevines.

The work is done under the development of an Agri.Q mobile manipulator for precision agriculture [38], that is a lightweight rover with self-charging capabilities thanks to solar panels and the related orientation mechanism [39] that allows us to properly orient them to increment the collect the solar radiation. To interact with the environment, the rover is equipped with the commercial Kinova Jaco2 arm [40,41], a 7 d.o.f. (degrees of freedom) assistive manipulator here used for grapevine sampling.

The tool is specifically designed to not entirely substitute the standard commercial gripper, it is lightweight, easy to manufacture, and it does not introduce any additional motors or the drive chain, thus moving towards a modular scenario where the interacting ability of the manipulator is preserved, but it can be eventually augmented by the means of an autonomous mounting procedure of the tool upon the gripper fingers. To make the work accessible to other interested researchers, the tool can be manufactured with the use of standard 3D FDM printing machines and customised with additional components. Moreover, even though the arm-tool interface is specific to the under-examination robotic manipulator, the functional and executive design methods are of general use and can be easily adapted to different scenarios.

The following chapters are organized as follows:

- In Section 2, the design requirements and the functional design of the system are presented.
- In Section 3, the functional architecture is converted into an executive design, also showing the prototype final version.
- In Section 4, a preliminary experimental validation of the system is given.

2. Concept and Functional Design

In general, a single harvesting operation can be conceptually seen as a pick and place operation where the pick operation is the composition of the picking and cutting of the peduncle. For this reason, the main requirement of the tool under investigation is the ability to perform the picking and cutting of the peduncle based on a single input: the motion of the end-effector gripper. Since the harvesting tool must be held by a generic manipulator, its compactness and lightness are of paramount importance. Towards this goal, a simple architecture with a limited number of metallic components, e.g., springs, screws and pins, is more suitable for the application. Another fundamental requirement for the system is its adaptability to different grapevine peduncle sizes, generally up to a diameter of 8 mm. In this context, adaptability means the ability of the tool to perform the picking and cutting operations with the same holding resultant force applied to the peduncle. For this reason, the tool concept is centered around the idea of decoupling the picking motion from the cutting one. In Figure 2, an illustration of the selected functional architecture is illustrated, with two different configurations, one with a traction spring and one with a compression spring, but from a purely functional point of view they are equivalent, thus the following description of the concept functioning applies to both configurations. In order to allow for the reach of the peduncle in case of dense foliage, the scissor-like architecture is employed [33,35].

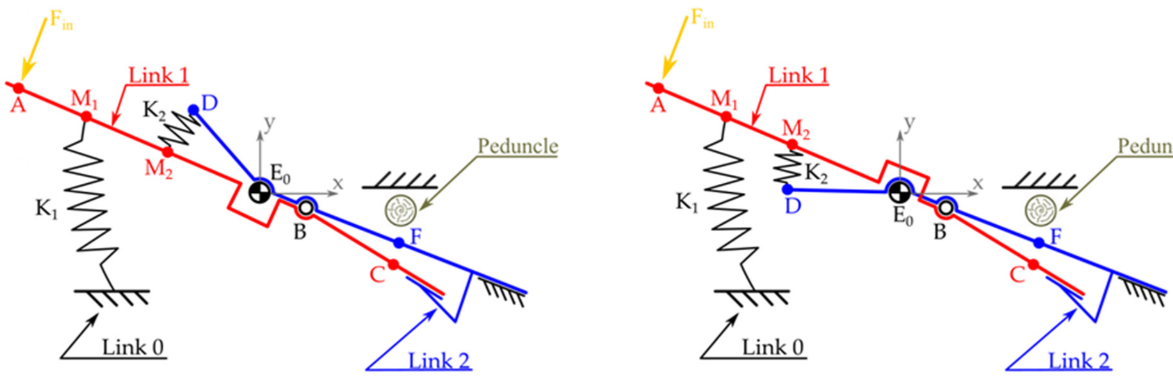


Figure 2. Functional representation of the proposed tool. For modelling purposes, Link 0 is depicted as fixed. (**a**) Configuration with a traction spring, (**b**) configuration with a compression spring.

In the following, the main components of the tool are presented. Link 0 and Link 1 are the input links, i.e., the links on which the input forces will be applied by the manipulator gripper fingers. At the distal end of Link 1, the cutting blade is installed (point C). Link 2 is connected to Link 0 through the revolute joint E_0 and to Link 1 through the revolute joint B. The picking operation is performed between the distal ends of Link 0 and Link 2, while the cutting one is achieved through the relative motion between Link 1 and Link 0. A torsional spring of stiffness K_1 is interposed between Link 0 and Link 1, while a secondary spring (that may be a traction or a compression spring) of stiffness K_2 is interposed between Link 1 and Link 2. As it will be further illustrated, by tweaking the preload force of the spring K_2, the peduncle holding force can be adjusted.

It is worth underlining that, for modelling purposes, Link 0 has been considered fixed, and so it is represented in the illustrations, and all the input motion is attributed to Link 1, as the system is observed by a reference frame that is fixed to Link 0. However, observing the system by a reference frame that is fixed to the manipulator end-effector, both Link 0 and Link 1 move and their relative motion is the input motion itself. Since the secondary spring K_2 is the preloaded, Link 1 and Link 2 rotate rigidly around the revolute joint E_0 during the first phase of the closing motion. When a certain value of picking force, applied between Link 2 and the peduncle, is reached, Link 2 stops rotating around E_0 and Link 1 starts rotating relative to Link 2 around the revolute joint B. As the motion proceeds, the cutting phase can be achieved while maintaining a certain holding force between Link 2, the peduncle and Link 0. It is straightforward that, by varying the preload on the secondary spring, the holding force can be adjusted. Moreover, the configuration of the system when it is not actuated is ruled by the elastic forces of the two springs and the support reactions of the two end stops, as illustrated in Figure 2a.

Based on this architecture, a parametric analysis has been performed to evaluate the influence of the geometric parameters on the input/output gain. To perform this analysis, the nomenclature presented in Figure 3 has been introduced. In particular, point A is the point where the resultant input force F_{in} is applied to Link 1 by the manipulator gripper fingers, and it is imposed as normal to the Link 1 direction during the motion; the resultant picking force F_p is applied at point F on Link 2; point C is the point on Link 1 where the resultant of the cutting force F_c is applied; and point M_1 and point M_2 are the attachment points on Link 1 of the two springs. To better evaluate the impact of the different parameters on the input/output gain, a dimensionless study of the model has been performed. In particular, the geometry of the tool has been parametrized over the parameter b_1, i.e., the lever of the cutting force with respect to the revolute joint B.

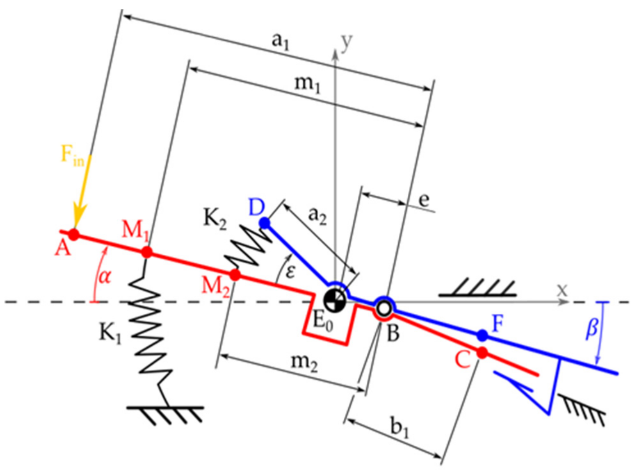


Figure 3. Functional scheme of the tool during its motion with the adopted nomenclature. The motion of the system is described by the rotation of Link 1 and 2 with respect to Link 0, represented as fixed.

The objective of this parametric analysis is the evaluation of cutting gain G_c, defined as:

$$G_c = \frac{F_c}{F_{in}} \tag{1}$$

From the rotational equilibrium of Link 1 relative to B, the gain can be expressed as a function of the geometric parameters:

$$G_c = \frac{F_{in}\, a_1 - F_{M1}\, m_1 - F_{M2}\, m_2}{b_1\, F_{in}} \tag{2}$$

where $F_{Mi} = K_i \Delta l_i$, $i = 1, 2$ and Δl_i are the elongation of the spring from the unloaded configuration. Because of the practical objective of this parametric analysis, the following assumptions have been made based on the practical considerations:

- Maximum angular distance between the input links $\alpha_{max} = 35°$;
- Minimum angular distance between the distal ends of Link 1 and 2 $\beta_{min} = 20°$;

$$K_2 = 1\, N/mm,\ K_2 = 0.4\, N/mm$$

during the parametric analysis, the influence of the following geometric ratios has been considered: $R_{a1} = a_1/b_1$, $R_{m1} = m_1/b_1$, $R_{a2} = a_2/b_1$, and $R_e = e/b_1$. The results are briefly presented in Table 1. As expected, an increase in the ratio R_{a1} results in an increase in the gain G_c while all the other ratios have opposite effects.

Table 1. Evaluated dimensionless parameters for the functional design of the tool and their effects.

Parameter	Considered Range	Effects on G_c
$R_{a1} = \frac{a_1}{b_1}$	From 2 to 10	↑ Increases
$R_{m1} = \frac{m_1}{b_1}$	From 1 to 3	↓ Decreases
$R_{a2} = \frac{a_2}{b_1}$	From 1 to 5	↓ Decreases
$R_e = \frac{e}{b_1}$	From 0 to 0.8	↓ Decreases

To obtain the final geometry ratio of the functional scheme of the tool, a trade-off between the necessary high gain between the input force and the output cutting force and the requirement of the compactness must be achieved. For this reason, the following geometric ratios have been selected: $R_{a1} = a_1/b_1 = 6$, $R_{m1} = m_1/b_1 = 2$, $R_{a2} = a_2/b_1 = 2$, and $R_e = e/b_1 = 0$.

To determine all the dimensions of the tool under analysis, a value must be assigned to the scaling parameter b_1. The value of 20 mm has been selected according to the scale of the Agri.Q manipulator, which results in the following dimensions: $a_1 = 120$ mm, $m_1 = 40$ mm, $a_2 = 40$ mm, and $e = 0$ mm.

3. Executive Design and Prototyping

Once the main geometric parameters have been defined, the executive design of the tool has been developed. In accordance with the methodologies of rapid prototyping, a first device has been designed and manufactured to validate the functionality of the architecture previously described with particular attention to the decupled pick and cutting motions. Moreover, the first prototype has been conceived to test and compare the functioning of the device with a traction spring and with a compression spring. After validating the effectiveness of the device, the interface between the tool and the robotic arm gripper was developed.

In Figure 4, the design of the first prototype is illustrated in the two configurations: with a traction spring (a) and with a compression spring (Figure 4b). As mentioned before, the whole device is conceived to be manufactured with conventional 3D FDM printers and the standard commercial components. To reduce the number of components to be 3D printed, Link 0 includes both the end stops for configurations (a) and (b) and Link 1 includes both the preloading regulation of the compression spring and the holding support for the traction one. With this approach, four 3D printed components are enough to test the tool both in configuration (a) and (b). The cutting operation is performed with the commercial blade and counter blade, the former installed on Link 0, while the latter on Link 1, both fixed through shape couplings and fixing bolts. Some soft material has been included to improve the holding ability and better adapt to the irregular shapes of the peduncle. All the revolute joints have been realized with economic techno polymer bushings to reduce the friction. The assembled prototypes are presented in Figure 5. With this manually actuated version of the harvesting tool, the correct functioning of the decoupling system has been validated. From these preliminary tests, the configuration (b) with a compression spring resulted in being fitted to the application. In fact, the higher encumbrance due to the traction spring resulted in the reduced ability of the tool to work inside dense foliage. Therefore, configuration (b) has been chosen for the final version of the harvesting tool.

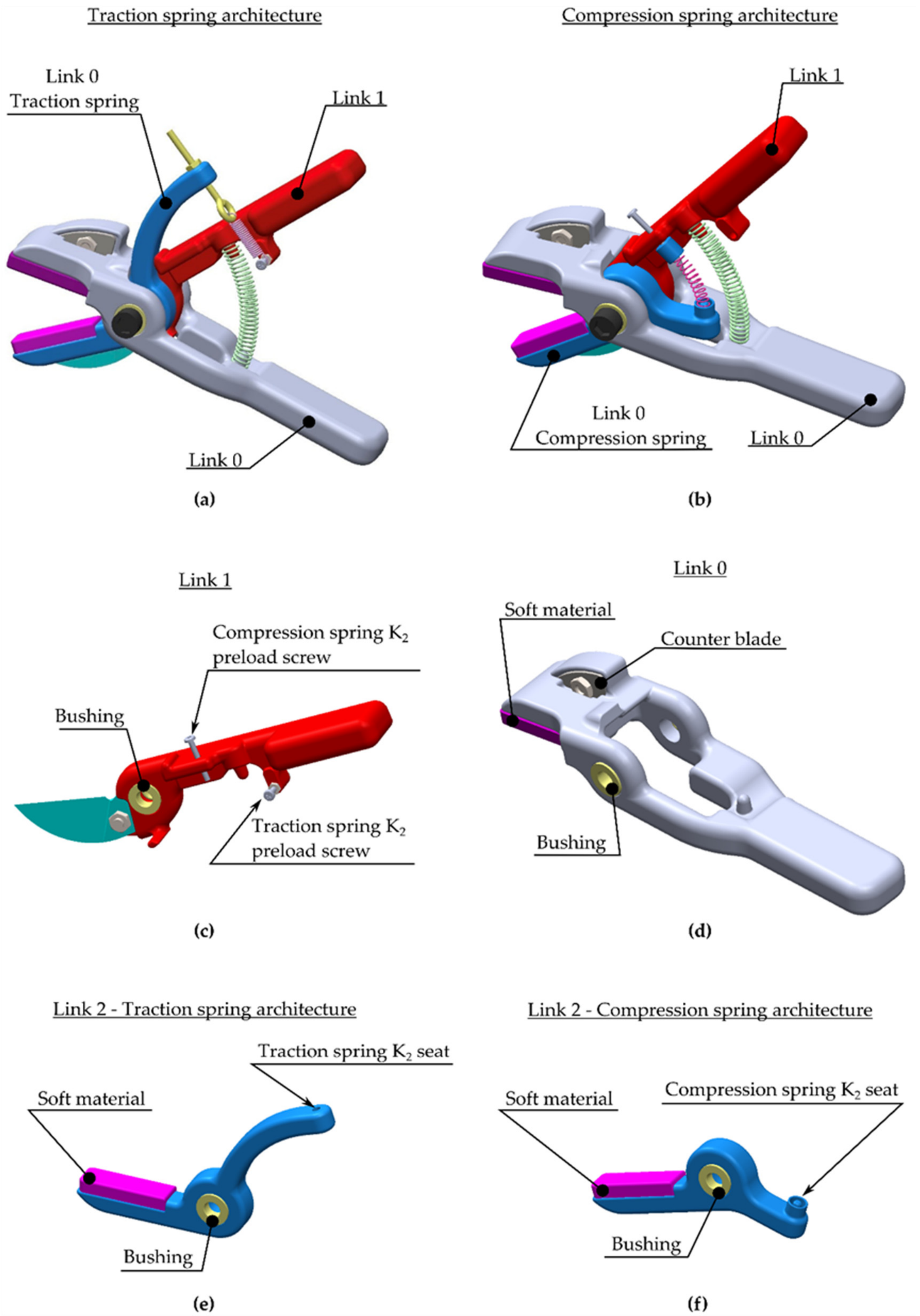


Figure 4. Executive design of the tool first prototype in the configurations with a traction spring (**a**) with a compression spring (**b**); detailed representation each subassembly: Link 1 (**c**), Link 0 (**d**), Link 2 with traction spring (**e**) and with compression spring (**f**).

(**a**) (**b**)

Figure 5. First protoype assembled in two configurations: with traction spring (**a**), with compression spring (**b**).

Robotic Arm Interaction

The second phase of the harvesting tool executive design focused on the interface between the tool and the robotic arm gripper, that has been designed for the specific gripper used in the application, i.e., the two-fingers gripper of the KINOVA Jaco 2 mounted on the rover Agri.Q. The same approach may be nonetheless used for different applications, with a simple change in the interface's geometry. For this reason, the executive design models, developed in SOLIDWORKS 2021, are provided open-source by the authors (https://github.com/Seromedises/IPAgriTool.git, accessed on 25 November 2022), together with the ".3mf" files, developed in Ultimaker Cura 4.12.1, containing all the details about the materials and printing properties.

Figure 6 presents the interaction of the robotic arm and the final prototype of the harvesting tool. Above all, the gripper itself requires a few insights. It is an under-actuated mechanism, in which two different lead screw motors are adopted to move the two fingers, each composed of two phalanges, respectively the proximal and the distal one, connected through two passive virtual revolute joints [42].

Based on this knowledge, the main idea was that of exploiting the under-actuation of the gripper to achieve a solid grasp of the tool. More specifically, the interface geometry has been designed in a way that the interface and the proximal phalange are coupled surfaces with little clearance, thus even a slight closing of the proximal phalanges ensures a well-established tool grip (Figure 6a). Afterwards, since the proximal phalanges are locked to the tool interface and cannot rotate anymore, during the closing of the fingers, the distal phalanges rotate with respect to the proximal ones until they come in contact with the upper surface of the tool interface itself (Figure 6b). In this way, the relative motion between the proximal and distal phalanges is locked and the gripper becomes a one d.o.f. mechanism. To prevent the tool from an out-of-plane rotation, lateral supports have been added to the interface. By considering the positioning accuracy of the arm, that is around 1 mm over the entire workspace, the correct functioning of the procedure can be guaranteed with little clearance of the tool mounting, that does not affect its functionality.

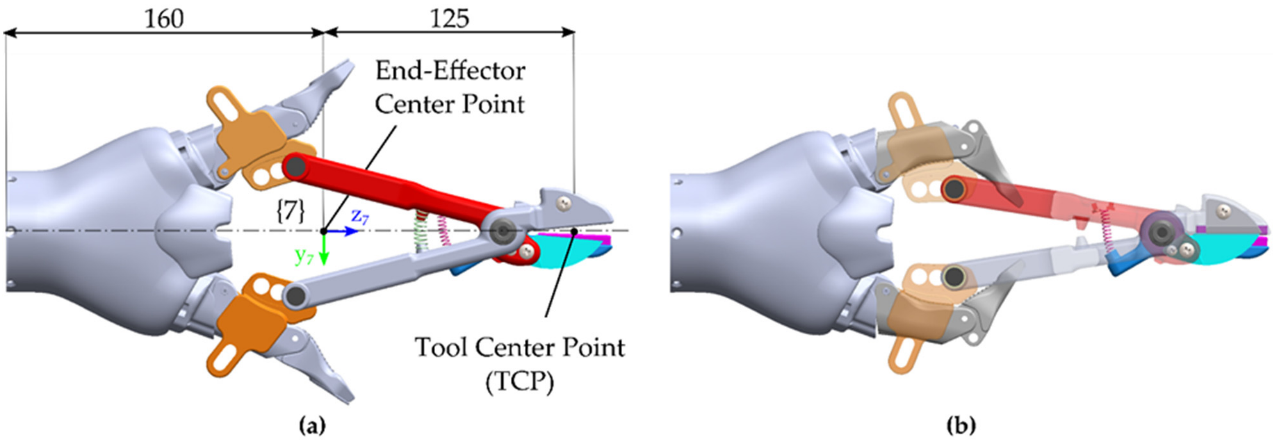


Figure 6. Tool mounting procedure upon the Kinova Jaco2 2-fingers gripper and TCP definition. (**a**) The coupled surfaces on proximal phalanges and interface ensures a first grip of the tool, (**b**) the rotation of distal phalanges until stop on the interface ensures the lock of the relative rotation between proximal and distal phalanges, thus making the system a one d.o.f. mechanism.

For the future automatic implementation of the harvesting task, the tool center point (TCP) of the proposed mechanism is defined in Figure 6a. The TCP lies on the z axis of the reference frame fixed to the end effector (frame $\{7\}$ according to the robot's documentation) and at a distance of 125 mm from the origin, also defined as the end-effector center point or end-effector position by the documentation.

4. Experimental Tests

To validate the functionality of the presented prototype, preliminary tests were carried out in a structured environment where the position and orientation of the grapevine peduncle were considered as known to the Agri.Q mobile robot planner. In particular, the grapevine was placed in a fixed and known position relative to the Agri.Q base frame. For this first experimental phase, the sensing system for the autonomous peduncle recognition and pose estimation has not been considered and the arm was controlled in a tele-operated mode. Nevertheless, a planning strategy based on the decoupling of the mobile base motion and the manipulator one has already been proposed for the planning of the mobile manipulator Agri.Q, and this strategy will be adopted in the final automatic procedure. This approach is beneficial due to the significant difference between the position accuracy of the two sub-systems, mobile rover and robotic arm. On this topic, the interested reader is addressed to the study [40] where the motion planning of the mobile manipulator has been analysed. Hence, if the position of the goal peduncle P_{goal} is supposed to be known with respect to the fixed frame $\{\mathrm{O}\}$, thanks to a generic sensing system, the base mobility, i.e., the pitch angle γ and the linear displacement s, is used to get the manipulator closer to the target. The intrinsic (or kinematic) redundancy of the manipulator itself is instead exploited to avoid foliage, the Agri.Q solar panel and other possible obstacles. If $\mathbf{T}^{\mathrm{O}}_{\mathrm{goal}}$ is the 4×4 homogeneous transformation matrix that describes the position and orientation of the goal peduncle with respect to $\{\mathrm{O}\}$, the decoupled motion approach can be formalized through the following equation:

$$\mathbf{T}^{\mathrm{O}}_{\mathrm{goal}} = \mathbf{T}^{\mathrm{O}}_{\mathrm{R}}(\gamma,\ \mathrm{s})\ \mathbf{T}^{\mathrm{R}}_{7}(\mathrm{q}_1,\ \ldots,\ \mathrm{q}_7)\ \mathbf{T}^{7}_{\mathrm{TCP}} \tag{3}$$

where:

- $\mathbf{T}^{\mathrm{O}}_{\mathrm{R}}(\gamma,\ \mathrm{s})$ represents the Agri.Q mobility and contains information about the arm mounting position;
- $\mathbf{T}^{\mathrm{R}}_{7}$ is the transformation matrix from the arm fixed base frame $\{R\}$ to the arm end-effector base frame $\{7\}$, and it is a function of its generalized coordinates $(q_1,\ \ldots,\ q_7)$;

- $\mathbf{T}^{7}_{\text{TCP}}$ contains the information about the geometric off-set between the end effector and the tool, as presented in Figure 6.

In Figure 7, a generic representation of the decoupled approach is presented, where the magenta line is the trajectory of the reference frame $\{R\}$, which is depicted in the initial $\{R_i\}$, final $\{R_f\}$ and intermediate $\{R'\}$ configuration.

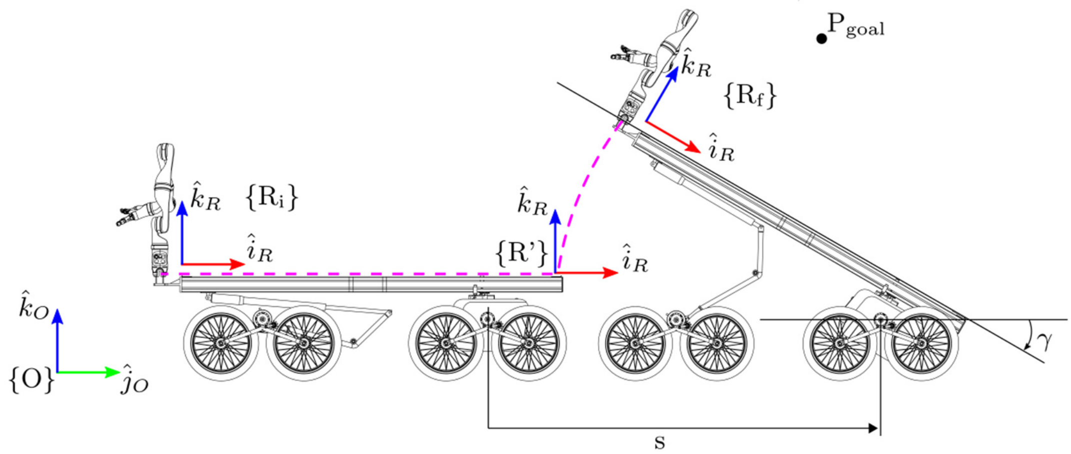


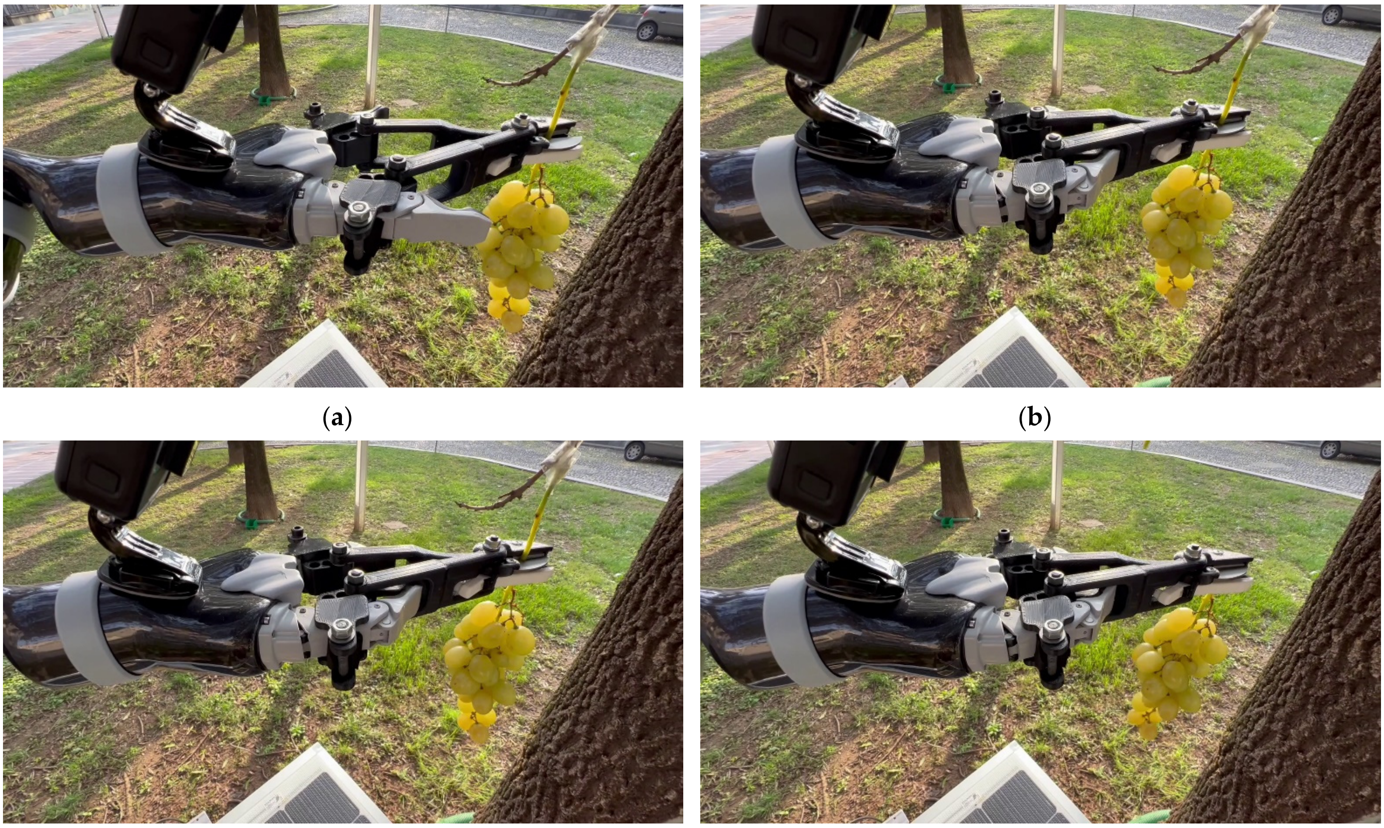
Figure 7. Representation of the decoupled motion planning approach. The magenta line represents the trajectory of the manipulator base frame $\{R\}$, P_{goal} is the target peduncle point.

During the test, the robotic arm is nonetheless tele-operated to reach the grapevine peduncle with the TCP. In this position, the fingers of the robot gripper are closed to perform the cutting and picking operation, and finally the grapevine is placed inside the box. In Figure 8, the Agri.Q prototype is represented before the cutting procedures. In this configuration, the Jaco 2 gripper holds the tool with the proximal phalanges.

(**a**) (**b**)

Figure 8. Experimental setup for the tool functionality tests. (**a**) Agri.Q whole system, (**b**) manipulator and scissor-like tool mounted on the gripper fingers.

A variety of grapevine peduncles have been used, with a maximum diameter of 8 mm. During the experimental phase, the preload adjusting system turned out to be a fundamental feature for the correct functioning of the device. In fact, a preload force trade-off value must be set in order to limit the required finger actuation forces, while providing enough picking force to hold the grape. After a preliminary setup phase to correctly adjust the preload, the system successfully completed the procedure with a 100% success rate, where a test is considered successful if the cutting is performed without problems and if the tool is able to hold the grapevines till the end of the storing phase. Moreover, it was checked that, even under acceleration values near to the manipulator joint motor limits, the tool can successfully hold and carry the grapevine. A graphical representation of the main phases of the experimental test is presented in Figure 9. The experimental tests also highlighted some drawbacks related to the stiffness of the main spring. In fact, too high values could require actuation forces above the maximum limit of the gripper, while too low values result in poor tool holding. As a reference, the current prototype has a main spring with a stiffness of 631 N/m. For this reason and to test the limit of the holding capability, some tests have been performed with an additional clamping screw to fix the interface to the gripper first phalange. Nevertheless, the feasibility of the passive interface has been proved. As a result of these tests, the tool was able to hold a grapevine (with a peduncle diameter of 3.2 mm) of up to 460 g in weight.



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

Figure 9. Tool functionality during the tests. (**a**) Peduncle approaching, (**b**) the distal phalanges are locked on the mounting interface thus making the system a one d.o.f. mechanism, (**c**) the soft material has grasped the peduncle and link 1 starts to rotate, (**d**) the peduncle has been cut and the tool holds it.

5. Conclusions

Towards the development of a mobile manipulator for precision agriculture, equipped with a set of tools that can be autonomously mounted and used by a robotic manipulator to interact with the environment, the functional design and test of a novel tool for the sampling and harvesting of grapevines have been presented. The main peculiarities of this tool are the adoption of an under-actuated mechanism to achieve the adaptability of the tool to different sizes and shapes of the grape peduncles and the use of a passive interface that could be grasped by a two-finger commercial gripper. In the literature, no architecture with these characteristics has been proposed for precision agriculture applications. To validate the fundamental functionality of the tool, a preliminary executive design has been made with the use of 3D FDM printing techniques and standard commercial components, thus making the prototype easy to replicate. Using a first set of grapevines with different peduncle diameter sizes and different required cutting and holding force values, preliminary experimental tests have been performed in teleoperated mode, assuming the peduncle position and orientation as known to the Agri.Q motion planner. These tests proved the effectiveness of the solution and highlighted some limitations of the current architecture. In particular, the robot equipped with the tool performed the sampling of a grapevine in a structured and controlled environment with a 100% success rate. The tests also highlighted some drawbacks of the passive interface between the tool and the robot gripper. These limitations, related to the stiffness of the main spring, will be the focus of further studies on the mechanism. To broaden the system ability to autonomously navigate and outperform different traditional precision agriculture tasks with the use of a set of interchangeable tools, an automatic procedure for tool mounting and peduncle cutting will be further developed and validated. When the procedure will be completely automatized, the final steps will be to evaluate the performance of the tool, in terms of the precision, repeatability, resolution and efficiency. Such evaluations cannot be made at this stage since all those properties are strictly dependent on the performance of the entire automatic system.

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Conflicts of Interest: The authors declare no conflict of interest.

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