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Design and Preliminary Testing of a Novel Semi-automatic Saffron Harvesting Device

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Abstract. This paper addresses the procedure for designing a novel mechatronic device for a semi-automatic saffron harvesting. The design process includes the kinematic analysis and synthesis of the proposed mechanism to fulfill a grasping and harvesting of saffron flower with a specific two-finger gripper design. Then, a cam mechanism and elastic spring elements are designed to provide a shaking movement that achieves the splitting of the flower from its steam and a consequent flower harvesting. This is followed by a suction system for collecting and storing the harvested flowers. A 3D printed prototype is reported and preliminarily tested for validating the engineering feasibility and effectiveness of the proposed design solution.

Keywords: Mechatronic design · Saffron harvesting · Grasping

1 Introduction

Saffron is an important edible spice, which is used in several regional and international meals [1]. The production of saffron requires a complex process, which is mostly handled by manual workers, who need to bend their back for a significant amount of time with high discomfort and pain. Multiple attempts have been made to automatize the harvesting process. Some examples are reported in [2–7], showing semi-automatic and automatic systems with focus at the design of a specific end-effector, which plays a key role in mechanical harvesting of horticultural products as mentioned for example in [8, 9]. In literature many studies are available on the design of the End-effectors design for robotics harvesting, but they are always designed for single-product applications [10–13]. This circumstance occurs again in mechanical harvesting of saffron, which is particularly challenging due to the high fragility of saffron flowers.

This paper addresses the design of a novel mechatronic device for a semi-automatic saffron harvesting, which need to be simple and economical, with productivity comparable to a human operator, and consequently with low-costs, ergonomic, transportable,

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light, and autonomous, for upright position use. In particular, in the following Sects. 2 and 3 focus at the design requirements and conceptual design of proposed solution, respectively. Section 4 focuses at the design of a prototype. Finally, Sect. 5 shows the rapid prototyping and preliminary experimental validation to demonstrate the main functioning principles of the proposed device.

2 Functional Analysis and Design Requirements

Table 1 reports a list of main requirements to be achieved with a proposal of solutions to fulfill them. The attached problem can be divided into two distinct parts. Namely, there should be a mechanical element (End-effector) that is able to make the cut on the stem without damaging the leaves, and an auxiliary device capable of allowing the movement and storage of the flowers.

Once the flower has been separated from the plant, the second device will take the object from the work area and store it. Thanks to the great lightness of saffron flowers, it has already been seen how they are easily achievable through a suitable suction system. Placing the suction mouth near the work area of the mechanical element, the cut flower can be grasped by the air flow and transported inside the storage chamber.

Finally, the operator must be able to directly manage the devices, as well as some parameters such as the power delivery of the aspirator. This presupposes the implementation of a small control unit, easily reachable by the operator's fingers.

Table 1. Functional analysis of the proposed device.

	What to do	How to do
End-effector	Include the flower	Without damaging the surrounding ones
	Stem cutting	The leaves must not be damaged.
Suction system	Flowers moving	Cut flower must be gripped without excessive stress.
	Flowers storage	No compression during transport.
Control unit	Units managing	Operator must be able to manage the device parameters

The main steps that will be followed to complete the entire design phase, and consequently define the tool, it can be summarized starting from the distinct definition of the two detachment systems and aspiration, up to the elements that will allow their interaction.

3 Conceptual Design

The proposed device can be imagined like a backpack brush cutter, with a moving part that can be associated with a modern garden blower. The entire system could be composed of two distinct units, connected however to each other through flexible elements. A first element, transported manually, will have the shape and size suitable to allow the operator to reach the flower without bending the back. At the lower end there will be both the End-effector and the mouth of the suction system. Through a flexible rubber tube, the cut flowers will be able to reach the storage area, and both the suction system and the tank could be housed in a shoulder-mounted structure.

Total weight must not exceed 5 kg The device must also have a fully electric power supply system, which can be powered by a battery, capable to guarantee the autonomy for the entire harvesting phase, and to be protected from external agents like rain. Finally, the system must have an average production cost, to be accessible by small and medium-sized enterprises, which are the principal producers of saffron. Table 2 reports a functional analysis for the proposed device summarizing the main expected characteristics.

Table 2. Functional analysis of the proposed device.

	Value	Notes
Harvest time	2–5 s/*flower*	Positioning, cutting, suction
Shape	Gardening tool	Manual unit and shoulder-mounted element
Weight	3–5 kg	Total weight
Implementation	Electrical	For suction system and end-effector
Power supply	18–40 V	Rechargeable electric battery
Autonomy	3–6 h	Half a working day
Materials	Aluminum – Plastic	Maybe rubber, fabric, or steel
Temperature	18 °C–28 °C	Room temperature
Work environment	Open field	Moisture, organic materials, rain
Production cost	300–500 €	Average cost range

A first constructive hypothesis could be represented by a simplification of the kinematics of the two-finger gripper presented in [7]. Two specular fingers with a suitably modeled terminal profile approach as the two elements are rotated, until they are close enough to guarantee the grip of the aerial parts of the plant. Once the rotation movement has reached the end of its stroke, and the flower will be correctly grasped, the gripping elements must rotate in order to subject the flower stem to a stress of traction. The simplest constructive choice can be represented by the exploitation of an elastic element, which releases all the accumulated energy at the appropriate time.

As for the suction system, the power used must be contained within a predetermined range, since excessive stresses along the path could damage the product, and at the same time a too weak air flow could not guarantee the correct capture of the flower. Consequently, the sizing of the vacuum pumps will be carried out starting from a simplified geometric model of the flower, to estimate its floating speed. Subsequently, once the suction duct has been sized, it will be possible to evaluate the total head losses along the entire path, and therefore to trace the required pump model.

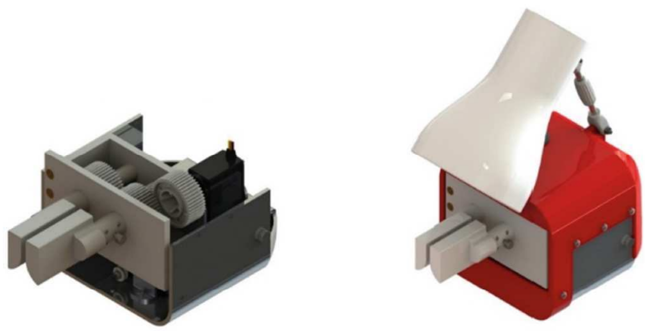
4 Dimensional and Mechanical Design

4.1 3D Modeling

The sizing of the gripping elements with the relative handling was carried out based on the existing solution. Two mirror fingers, like those used in [7], are placed at the ends of two transmission shafts integral with each other by means of two gear wheels of the same module and pitch circumference. The surface of the two fingers has been modeled in such a way that during the rotation phase they remain at a fixed distance of 1.5 mm. A wheelbase regulation system allows to adapt this distance between the two grasping surfaces at the variability of stem diameter.

The housing for the grasping elements consists of a front plastic element with two holes for the passage of the fingers, and a rear plate, which presents a revolute joint on the back side that will be used to create the hinge to generate the traction of the flower. A series of leaf springs are directly realized from an element in aluminum, that had also function of houses.

A plastic external body was created to protect the End-effector internal components from external environment, essentially composed of two elements, which can be inserted one on top of the other. The external body of the End-effector will also be used to connect the instrument to the maneuver rod. The suction hood has been modeled as a separate element, connected to the external body by a hinge, and positioned exactly above the two gripping elements. On the back side, an adjustable length tie rod has been inserted. Figure 1 shows 3D CAD models with the main assembly for the proposed End-effector.



(a) (b)

Fig. 1. Assembly for End-effector: a) Internal part assembly; b) External part assembly

Modeling of suction system was made starting from the geometry and dimensions of the main elements, such as vacuum pumps and batteries. the suction system can be considered composed of two distinct bodies: a head, inside which all the electronic elements will be assembled, as well as the outlet of the suction duct, and a storage compartment, which will represent the real tank of the system under consideration, with a capacity of 14 L. The two elements, which can be easily assembled by means of two toggle closures, will form the entire shoulder-mounted structure.

Gear Sizing. The distance between the central axis of the two shafts must be equal to 33.60 mm, and this leads us to define the primitive radius of the two mirror gears, equal to 16.8 mm. Two gears with number of teeth and module respectively equal to 48 and 0.7 were chosen. Considering the operation of the latter over a 180° arc as a data plate, to avoid positioning errors or too long times, it was decided to insert an additional gear that would allow to obtain a transmission ratio $\tau = 0.625$ between shaft and motor, which will have a primitive radius of 10.5 mm, and a number of teeth equal to 36, and will also be integral with one of the two transmission shafts. The pinion connected directly to the servomotor will act on this last element. In this way it will be possible to limit the maximum travel of the servo to an arc of 112.5°, obtaining a rotation of 180° on the two fingers.

Motor Sizing. The first servomotor can be sized starting from the simple equation of equilibrium to the rotation of the moving elements. Neglecting the former, the magnitude of the moments of inertia, evaluated once the 3D design phase has been completed, was found to be sufficiently low not to constitute a relevant factor for the choice of the servomotor. As for the sizing of the second servomotor, the force value imposed during the design phase of the elastic charging system was equal to 50 N, and consequently the choice of the servo can only fall on a model that is able to guarantee the necessary torque value, equal to 0.3 Nm. Then, it will suffice choose a pair of servomotors of the same model, which reflect the specifications imposed.

Figure 2 shows 3D CAD models with the main assembly for the proposed Portable Collecting Device.

(a) (b)

Fig. 2. Portable Collecting Device; a) front view; b) back view.

4.2 Cam and Leaf-Spring Design

Starting from the strength or displacement value necessary to stress the stem of the flowers until they break, it would be possible to sizing the leaf springs. Unfortunately,

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no data in this regard was available in the literature, and an experimental determination was impracticable. Consequently, it has been necessary to start from presumed values, hypothesized based on the information collected from the in-depth study of the plant in question and of the existing systems.

A loading force of 50 N was chosen as a reference value, which was sufficient to generate an arrow of 1 mm on the free end. To ensure that the Bernoulli theory on the bent beam was respected, the best option was to insert several leaf springs, arranged in parallel, and to be considered as a single elastic body.

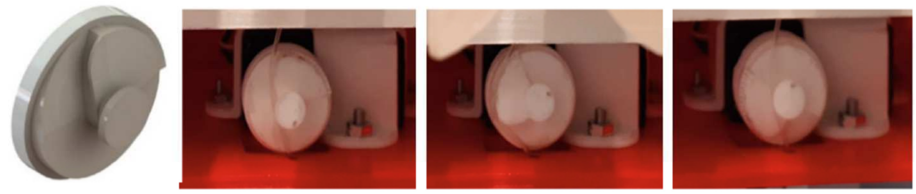
From the definition of stiffness of the bent beam and through the expression of the arrow (Eq. 1), it was possible to go back through iterative calculations to the number of sheets needed, as well as to the values of thickness, length and width of the single sheet, considering how material an aluminum alloy that had an elastic modulus of 69000 Mpa The result led to the definition of a number of 5 springs, arranged in parallel, and with geometric dimensions equal to $3 \times 15.2 \times 90$ mm as summarized in the 3D CAD model shown in Fig. 3.

Fig. 3. Aluminum element with leaf spring.

$$F = n\frac{3EI}{L^3}y \tag{1}$$

The traction tension will be applied by a nylon thread, through an innovative cam system modeled appropriately for the proposed purpose (Fig. 4). With this solution, one end of the nylon thread will be connected to the main plate of the grip block, while the other will be rigidly connected to the structural case. In this way the wire, which at rest will be in a vertical position, will always have its axis tangent to the profile of the cam.

Carrying out a first rotation of the cam of 90° counterclockwise, it is able to put the wire in traction for the time necessary to perform the gripping operation, then allowing its instantaneous release once traveled the next 90°. Once the trigger has been made, the servo will be able to return to its initial position without involving the wire in any way, indeed returning the cam to the condition of being able to re-engage it if the next operation is to be performed.



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

Fig. 4. Cam system: a) CAD model; b) wire hooking in the first handling phase; c) wire traction and leaf-spring loading; d) wire snap and elastic energy releasing.

5 Preliminary Experimental Test

5.1 3D Printing and Assembly

Through 3D printing technique, a prototype of the End-effector was created by CAD models created during design phase. As a raw material, polylactic acid (PLA) was used for 3D printing such as proposed in [14]. Components such as servomotors, elastic plates, or connection systems such as screws, nuts and inserts, were found through the purchase, if the accidental availability was not present.

5.2 Preliminary Experimental Validation

Much of the instrument's efficiency strongly depends on the good calibration of the bending movement that the End-effector performs once the two fingers have grasped the stem of the flower. To investigate the dynamics of this movement in greater depth, paying particular attention to the accelerations reached following the release of the traction wire, it was decided to carry out experimental measurements on the prototype using an accelerometer. The FXLN8371Q analog triaxial accelerometer, manufactured by Freescale Semiconductor, Inc, with a selected sensitivity range of ± 2 g was used as the sensor. The instrument was positioned on the front side of the End-effector (Fig. 5), in such a way as to obtain the x and y axes lying on the plane parallel to the front structural plate, with the outgoing z axis.

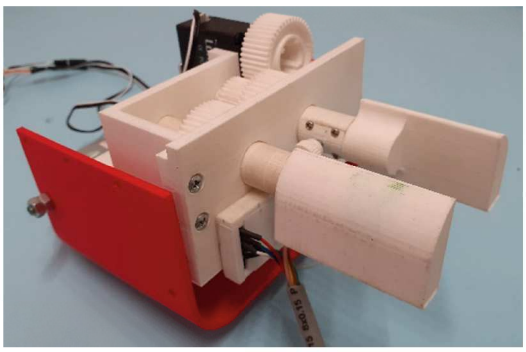


Fig. 5. Final prototype and accelerometer positioning.

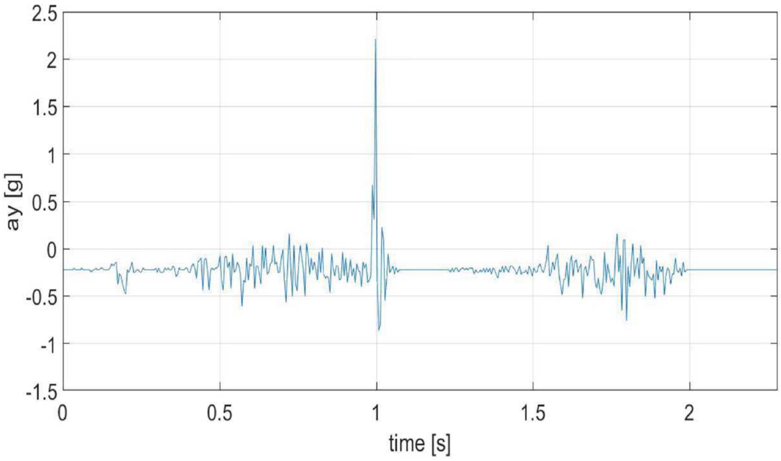
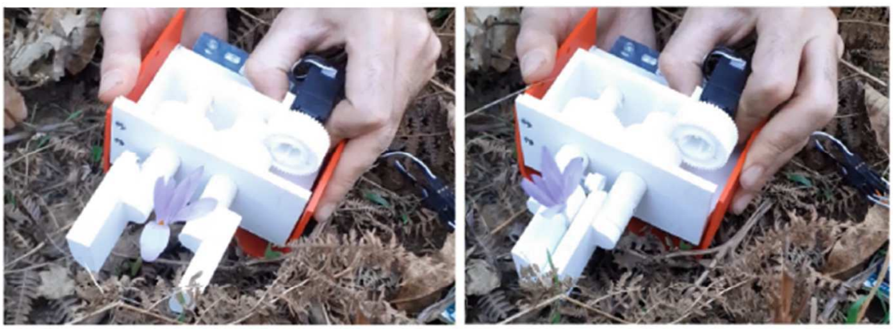


Fig. 6. Plot of y-axis acceleration.

A series of measurements were carried out by putting the End-effector into operation, over a time interval that embraced the entire movement phase of the two servomotors. In this way it was possible to obtain the data relating to the accelerations that develop on the gripping system, following traction with consequent release of the wire by the second servomotor.



a) **b)**

Fig. 7. Preliminary field tests on wild saffron flowers: a) approaching to a saffron flower; b) harvesting a saffron flower.

Important results were obtained on y-axis, Fig. 6, where it can be observed an acceleration peak that exceeds the value of ± 2 g. This data is representative of the instant in which the cam releases the traction wire, allowing the gripping system to snap upwards. Preliminary field tests were performed on wild saffron flowers, Fig. 7, highlighting the need for a pre-industrial prototype, with optimized specifications and features compared to the current one laboratory version. Further experimental activities will be planned in future to systematically validate the effectiveness of the proposed device in terms of grasping features and for achieving a performance optimization such as proposed in [15–17]. Further field tests will be specifically planned to validate the achievable productivity rates with the proposed device.

6 Conclusion

In this paper the design with the consequent realization of a semi-automatic system for the saffron flowers harvesting were described. In particular, in Sect. 2 is presented a functional analysis of the device that will be proposed, starting from a list of main tasks to be achieved by the system. In Sect. 3 the problem is divided into two distinct part, concerning respectively the End-effector for cut the saffron flowers and the shoulder-mounted suction system for collecting and storage them. In Sect. 4, the design phases led to an End-effector with two fingers, characterized by a mechanism capable of performing a rapid snap-folding movement on the gripping system, thanks to five leaf springs, preloaded by a nylon thread put in traction by an innovative cam system. Section 5 shows experimental validation of proposed device, carried out by an accelerometer, and preliminary test on field, which confirm conceptual design. Further experimental activities will be planned in future to validate the achievable productivity rates with the proposed device.

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