Smart carving of hard-shell fruit with CO2 Laser

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Abstract

The application of CO_2 laser technology in food processing has gained significant attention due to its precision and adaptability. This study presents an intelligent system for carving hard-shell fruits, specifically acorns, to facilitate their shelling process. The proposed approach integrates real-time control and monitoring technologies to enhance precision and efficiency. A key challenge in acorn processing is the size and shell thickness variability, which complicates mechanical carving. The developed system employs a CO_2 laser to create precise incisions, ensuring optimal shell cracking during dehydration while preventing kernel damage. Experimental tests conducted at the Polytechnic Institute of Bragança identified optimal parameters—6 seconds of laser exposure at 40*W* power—for consistent and controlled carving. A thoughtful analysis system was implemented to assess pre- and post-carving conditions, enabling real-time adjustments to laser settings. This self-optimizing process improves the efficiency of the shell carving while reducing waste. The results demonstrate the feasibility of automated acorn carving using CO_2 laser technology, offering a scalable solution for industrial food processing with continuous control of the shell incision. Future research could explore advanced automation techniques to enhance system robustness and adaptability to different fruit types.

Keywords

CO_2 laser, Food processing, Smart carving, Acorn shelling, Automation

1. Introduction

The use of CO_2 lasers for processing nuts and other foods continues to evolve. Recent research has explored new optical configurations and control strategies to improve the precision and efficiency of cuts, as well as the integration of artificial intelligence systems for the automatic optimisation of the process. These innovations aim to expand the applicability of laser technology in the food industry, offering advanced solutions for carving and processing hard-shelled foods. Given this context, the present study aims to analyse and develop advanced strategies for the intelligent carving of hard-shelled fruits using CO_2 lasers, integrating real-time control and monitoring technologies to enhance the precision and efficiency of the process. The goal of carving the acorn shell is to facilitate its shelling during the subsequent dehydration process, where it will be exposed to a temperature differential that creates mechanical stresses in the shell. This carving will help concentrate these stresses, leading to the natural cracking of the shell. Using CO_2 laser technology as a carving mechanism will address one of the main challenges in acorn shelling: the lack of size homogeneity between different species and fruits. Such heterogeneity hinders the possibility of developing a mechanical carving machine due to the difficulty of calibration from acorn to acorn. This issue is resolved with CO_2 laser carving and its innovative system, which analyses each acorn before and after carving, collecting parameters to adjust the laser settings instantly. The laser carving test conducted at the Polytechnic Institute of Bragança resulted in the best configuration for carving an acorn: 6 seconds and 40*W* of power exposure.

2nd International Conference on Smart Automation & Robotics for Future Industry, April 03-05, 2025, Lviv, Ukraine

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2. Objectives

This article refers to one of the main objectives of the Medacornet PRIMA/0005/2022 project: to develop a continuous acorn industrial processing line. This article will describe the development of intelligent equipment for carving the acorn fruit shell. The acorn shell and core have economic value. A precise carving avoids damage to both. An intelligent system was implemented to calibrate each acorn's most adequate carving parameters through a self-taught process. The CO_2 laser carving technique was investigated and evaluated to automate the carving of acorn shells in the food industry, selecting and experimenting with different laser parameters.

The specific objectives included designing and developing a feeding and positioning system that guarantees the product's entry into the carving line process, positioning and moving the acorn, certifying the correct longitudinal positioning of the acorns during the carving process, figure 1.

Determining the optimal carving parameters was the secondary objective. The goal enticed evaluating laser parameter settings to achieve a precise carving without damaging the kernel of the acorns, *i.e.* avoiding complete cutting of the shell and nipping the fruit's core, also avoiding excessive burning of the shell during carving. These parameters were tested in practical tests that verified feasibility and accuracy, encountered the proper parameters, and specified how the modification of these parameters influences the milling.

Figure 1: Position of the intended longitudinal carving on the acorn

3. State of art

Laser technology in food processing has emerged as an innovative alternative to improve efficiency and productivity in various industrial applications. In particular, the carbon dioxide (CO_2) laser has been proven to be a versatile tool due to its high power generation efficiency and wavelength in the infrared spectrum, which is strongly absorbed by water, the main component of food [1]. The characteristic of CO_2 lasers is that they emit radiation in the infrared spectrum, specifically around 10.6 μm. They excite a gaseous mixture of carbon dioxide, nitrogen, and helium, generating a continuous or pulsed high-power laser emission [2].

Patel developed the first CO_2 laser in the 1960s to find more efficient lasers using the vibrational-rotational transitions of gaseous molecules [1]. This technology has been applied to various food processing areas, including marking, micro-perforation to improve mass transfer operations, cutting and shelling, selective cooking, and microbial surface decontamination [1]. Among these applications, removing nutshells using lasers has attracted particular interest due to the need to reduce costs and improve the quality of the final product.

One of the most significant advances in this field was the invention and patenting of a method for removing nutshells using a CO_2 laser beam, developed by Chandra K. N. Patel in 1982 [3]. This method involved rotating the nut within the path of the laser beam to achieve a precise cut along a closed path, separating the shell into segments without damaging the internal seed. A second low-power laser beam with a specific wavelength was incorporated to optimise process efficiency, allowing differentiation between the shell and the seed through variations in their reflectivity. In this way, the system could automatically detect when the cut was complete and stop the application of the high-power laser. An inert gas jet also dissipated combustion residues, minimising beam attenuation and ensuring precise and rapid cuts [3].

Due to their precision and quality, CO_2 lasers are vital in industrial manufacturing for cutting and drilling various materials, including metals and plastics. They facilitate high-quality welding of metals through localized fusion, ensuring minimal deformation. Additionally, CO_2 lasers are used for thermal treatments like surface hardening, enhancing material properties without altering their structure. Their precision also makes them perfect for marking and engraving, aiding in product customization and traceability in industries like automotive and electronics.

In addition to traditional industrial applications, CO_2 lasers have found innovative uses in the food sector [1]:

Cooking and Browning: Techniques using CO_2 lasers for precise cooking and browning of food have been explored, improving efficiency and controlling the organoleptic characteristics of products.

Selective Laser Sintering: This technique enables the creation of complex structures from food powders, opening up possibilities for producing customised foods with novel textures.

Carving and Micro-Perforation: CO_2 lasers are used for marking food products and creating micro-perforations that enhance subsequent processes such as infusion, marination, or drying, optimis- ing product quality and safety.

Some of the fundamental parameters in CO_2 laser carving [4], [5] are:

Laser Speed Parameter: Describes the movement of the laser head. Fast speeds lead to short exposure times, while slow speeds result in long ones. For highly detailed photo engravings on wood, the speed should not exceed 10%. This setting also affects the quality of the laser cut. Note that cutting and engraving speeds are not comparable. Essentially, cutting is slower than engraving. A "high" cutting speed is 10%.

Percentage of Power Used: High power is generally required for dark wood or stamp engravings, whereas low values are used for materials such as paper.

Power Used: The power parameter describes the output power of the laser, with 100% being the maximum power.

Pulses per Inch (PPI): The PPI parameter determines how many laser pulses per inch are used for engraving. A higher PPI means the laser performs more pulses per inch, resulting in smoother and more precise edges. However, it can also generate more heat, which may cause burns on sensitive materials.

4. Methodology

The process explores the internal stress of the acorn shell, which contracts during the drying stage due to water loss. Due to the longitudinal cut performed only in the shell, its contraction during the drying stage enables the fruit's core to be easily exposed, allowing a clean separation of shell and core, figure 2. Both will have different uses down the line. The benefits of a laser cut, or incision, solely of the shell are in the process's velocity, maintenance, and cleanliness. Alternative and commonly used mechanical cuts tend to present uneven results, producing unwanted cumulative dust in the equipment and increasing maintenance and cleaning factory downtime.

Figure 2: Shelling of the acorn with the help of the carving process

A plan divided into two main stages was developed for an automated system of longitudinal carving with a CO_2 laser on acorns to favour their shelling, figure 3: The design of a positioning and feed system to place the acorn along the carving line; and the experimental analysis of the CO_2 laser carving parameters. The schematic representation in Figure 3 shows the processing expected by the Acorn Carving Machine, where the acorns continue to move (1) towards the CO_2 laser (2), generating the surface carving (3), which will then carve, separating shell and core in the dehydration process (4).

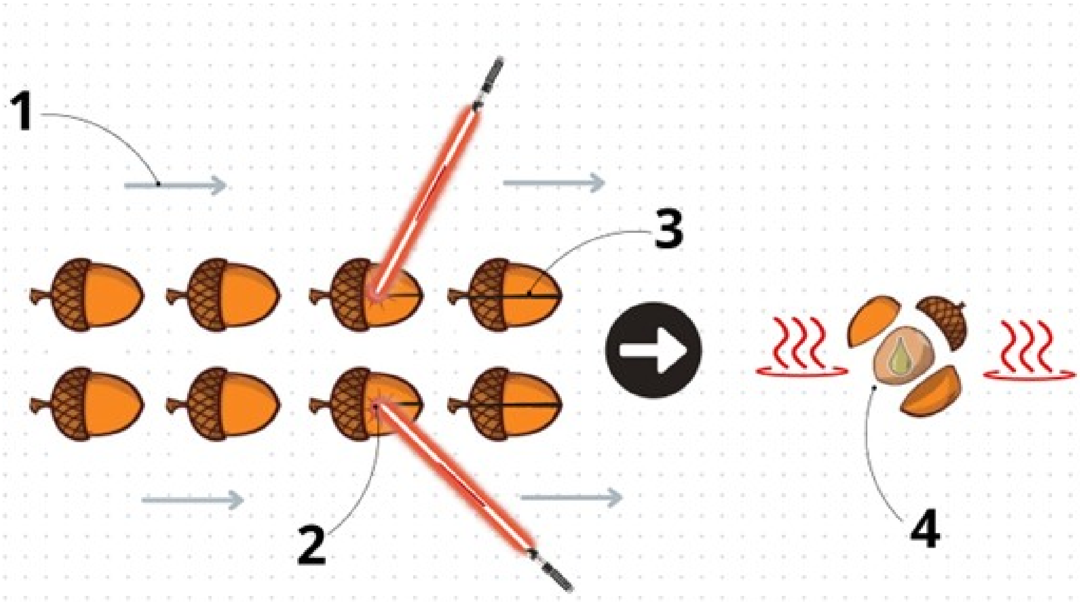

Figure 3: Desired line of acorn carving process

4.1. Supply and positioning system design

An automated system was designed, including a vibrating table for the uniform and controlled feeding of the acorns, a conveyor belt with an appropriate profile to align the acorns longitudinally, and one strategically placed CO_2 laser tube.

4.2. Determination of Carving Parameters

As mentioned in Section 3, the experimentation was based on varying one of these variables while keeping the others constant:

— The laser speed parameter
— Percentage of power used

4.3. Laser carving tests

The tests were conducted in the FabLab laboratory at the Polytechnic Institute of Bragança (IPB), which houses a CNC machine, the Portlaser X252, equipped with an 80 W CO_2 laser.

Acorns collected from the Santa Apolónia Campus (IPB) were used for the carving tests. The experiment proceeded by varying the operational parameters, such as the laser exposure time and the percentage of the power used, until the precise carving was achieved. The objective was to avoid completely cutting the acorn shell and prevent burning the area surrounding the carved section.

The output of this experiment is the optimal configuration that would ensure carving without burning the shell, confirming the use of lasers for this type of process.

Modifying the laser exposure time on the shell (laser translation speed) will make it possible to prevent the burning of the shell and core. The slower the speed, the longer the laser acts on the same shell area, increasing the likelihood of burning.

The carving depth can be controlled by adjusting the laser power. Excessive power would completely cut through the shell, potentially damaging the acorn's core, Figure 4.

Figure 4: Excessive use of power for carving

5. Results

The $C0_2$ laser acorn carving line developed in this article is represented in the block diagram, figure 5.

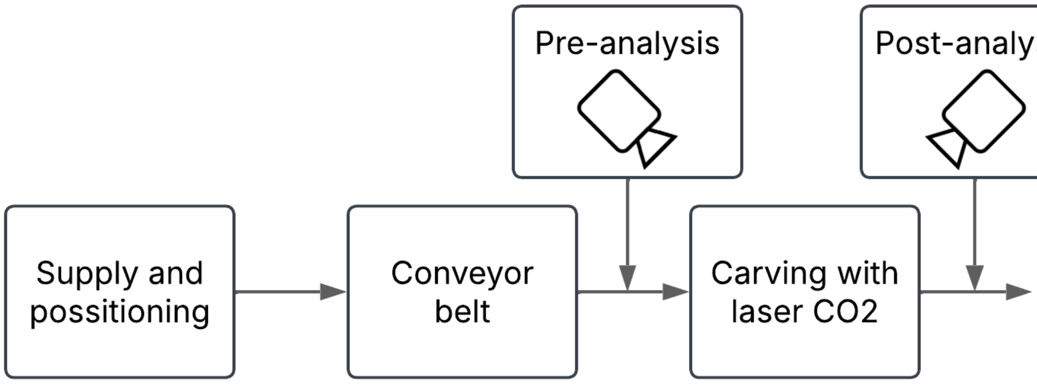

Figure 5: Carving line process

5.1. Supply and positioning system design

The feeding of the production line will include a mechanical pre-selection of the acorns, preventing those too large for the laser's power to carve and avoiding the introduction of unwanted materials such as stones and branches, as well as undesired organic material from the forests. This mechanical pre-selection was done by using a vibrating sieve with calibrated holes.

Once pre-selection is complete, the acorns dropped by gravity onto a conveyor belt. This belt must have a suitable profile to accommodate the acorns and position them to be ready for laser carving.

5.2. Determination of carving parameters

During the tests, the parameters were adjusted until an ideal result was obtained, which was achieved with an exposure of 6 seconds and 50% of the laser power ($40W$), figure 6, table 1.

Figure 6: Ideal acorn carving

5.3. Pre and post-carving analysis

The intelligent analysis system collects relevant information before carving, including dimensions and modelled shell thickness. Once the longitudinal incision is made with the laser, the system evaluates

Table 1
Carving results from the 80 W CO_2 laser for the acorn depicted in figure 6

Exposure time (*s*)	Power (%)	Power (*W*)
1.0	90	72.0
1.5	70	56.0
0.4	95	76.0
0.2	98	78.4
2.0	70	56.0
4.0	70	56.0
4.0	50	40.0
6.0	50	40.0

the quality of the carving and the ease of shell opening, providing feedback that allows the database to be optimised and the laser parameters adjusted for future iterations, figure 7.

The adaptive control of laser power (*W*), scanning speed (*mm/s*), and carving pattern helps minimise thermal damage to the kernel, reduce energy consumption, and improve the uniformity of the opening. Preliminary results indicate that the system can self-adjust in real time, improving carving efficiency with each production cycle.

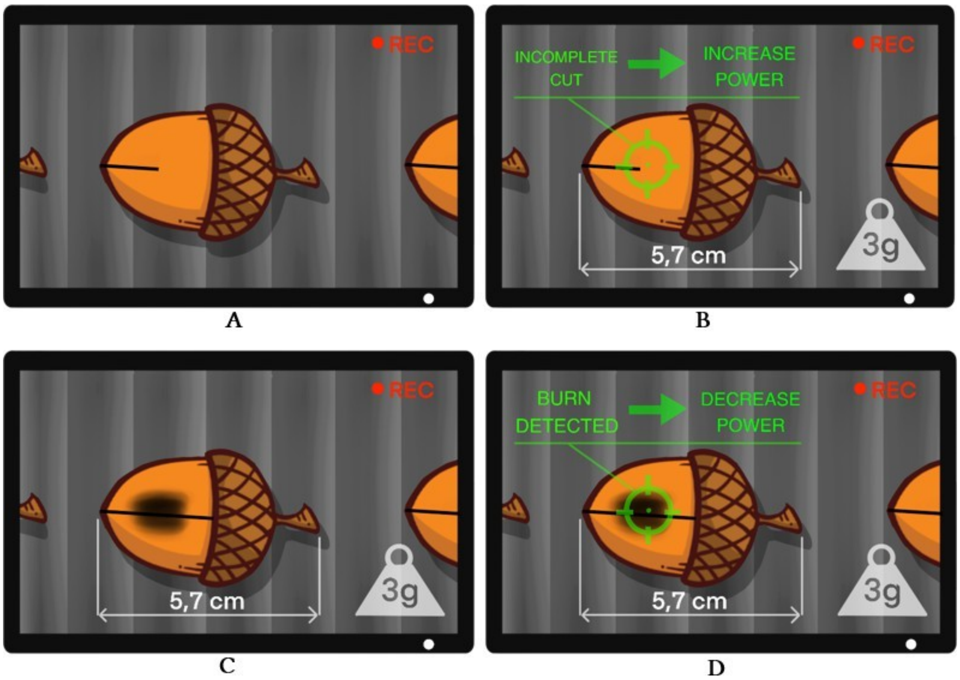

Figure 7: Sketch of the post-carving optical analysis

Figure 7 presents a sketch of the different decision-making of the Smart System, where after analysing the acorn, it can detect two possible problems; an incomplete carving, figure 7A and 7B, or a burnt shell, figure 7C and figure 7D.

After the prototype phase, the entire system for acorn carving using CO_2 laser technology is being designed and prepared for industrial implementation. This system aims to automate the carving process of acorn shells with precision and efficiency, ensuring minimal damage to the kernel. Integrating advanced sensors and an intelligent control system will optimise the process, adapting to each acorn's varying sizes and characteristics. The design phase includes the application of standard current off-the-shelf CO_2 lasers tailored for this application. Furthermore, the system is designed to seamlessly integrate into existing food industry production lines, providing a scalable solution for large-scale operations. By focusing on automation and precision, the system will not only improve the efficiency of acorn shelling but also enhance the consistency and quality of the final product, making it a viable solution for the food industry.

6. Conclusions

This research demonstrates the successful application of CO_2 laser technology in automating the carving of acorn shells. By integrating intelligent systems into the process, the research addresses key challenges, such as the lack of size uniformity in acorns and the need for precise carving to avoid kernel damage. The proposed approach optimises laser parameters, including exposure time and power, to achieve efficient and controlled carving, enhancing shell removal during subsequent processing.

One of the strengths of this work lies in the design of an automated system incorporating a vibrating table for pre-selection, a conveyor belt for proper alignment, and adaptive control mechanisms for real-time parameter adjustment. This setup ensures uniformity in the carving process while minimising thermal damage to the kernel and reducing energy consumption.

The experimental results validate the effectiveness of the optimised parameters—6 seconds of exposure time and 40 W laser power—in achieving precise longitudinal incisions without excessive burning or shell breakage. Furthermore, incorporating an intelligent analysis system enables pre- and post-carving evaluations, facilitating a self-optimising process that improves with each production cycle.

This research exemplifies the potential of CO_2 laser technology in the food industry and demonstrates the feasibility of automating complex processes. However, there is room for future exploration, such as implementing mechanisms to automatically discard unsuitable acorns due to size or shell burning, further enhancing the system's efficiency and robustness.

Aknowledgments

The authors thank Fundação para a Ciência e Tecnologia - FCT - I.P. through PRIMA/0005/2022, within the scope of the project MEDACORNET - Rescuing acorns as a Mediterranean traditional superfood.

Declaration on generative AI

In the process of preparing this paper, the authors utilized ChatGPT and Grammarly to identify and correct grammatical errors, typographical errors, and spelling problems. After using these tools, the authors have carefully reviewed and edited the content as needed and take full responsibility for the final publication.

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