VinPRO

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Executive summary

Today, vineyard pruning still relies heavily on skilled human labor. To address this, an increasing number of research initiatives are exploring the transition from traditional manual practices to fully autonomous robotic systems. The VinPRO project contributes to this effort by developing an **integrated robotic pruning platform** composed of a custom-designed gripper for vineyard environments, an advanced computer vision system to detect branches, a control algorithm to optimize cutting actions, and a virtual reality (VR) tool to model vines and simulate pruning strategies. At its core is a Kinova Gen3 Lite robotic arm, mounted on a mobile rover that serves as the physical backbone of the system.

To interface with the Kinova robotic arm without dismantling it, the team engineered a **lightweight 3D-printed housing**—a kind of mechanical "glove" that integrates the actuation mechanism for the pruning shear. They compared a pneumatic option with onboard compressed air and a compact electric motor with battery pack, ultimately selecting the electric solution for its reduced footprint and smoother integration with lab resources. An Arduino microcontroller translates control commands from the central system, triggering the cutting action.

With the mechanical structure in place, the focus shifted to modeling the vine's anatomy. Using a dataset of various grapevine images, the team developed a **deep learning-based pipeline** to detect nodes along the vine, classify branch and node types, and estimate spatial relationships among structural elements. For each input image, a directed graph is produced whose nodes have their own category, while edges correspond to the branches. Every node has at most one parent.

A **pruning policy algorithm** was developed to automatically select cutting points, which are converted into 3D coordinates and used as inputs to the control module. A motion-planning system guides the cutter precisely while avoiding collisions. Cameras on the gripper feed real-time images into the graph-generation engine, which identifies the necessary structures and passes them to the control module. The shear is actuated using ROS 2 libraries, which interface with the Arduino board. Once a cut is confirmed, the system proceeds to the next task.

To support human–machine collaboration, a **virtual reality interface** was developed. With detailed 3D models of vines—including trunks, branches, grapes, and leaves—the team built a virtual vineyard environment. This enabled the simulation of different growth scenarios, pruning strategies, and expected outcomes. The modular nature of the model allows for easy adaptation to different vineyard stages or training purposes.

Over two years of development, the VinPro project has successfully delivered a proof-of-concept system capable of modeling vine architecture through computer vision, planning and executing cuts with a robotic arm and precision gripper, learning and adapting through iterative control refinement, and simulating pruning operations in virtual environments. This work represents a significant advancement towards **semi-autonomous vineyard maintenance**, with the long-term potential to rival human expertise in precision and adaptability.

Figure 1: Robotic pruning end-effector mounted on Kinova Gen3 Lite arm.

Keywords

Robotic Vineyard Pruning, Process Automation, Computer Vision, Virtual Reality, AgriTech

Project description written by the Principal Academic Tutor

Vineyards represent a **high-profit agricultural sector** where precise robotics solutions are currently under research and development by both universities and leading companies. Winemakers and the entire industry of precision agriculture demonstrate a strong interest towards automation solutions that can lead to a more efficient and sustainable agriculture.

Pruning, however, is a challenging agricultural process that still needs to be manually performed to ensure a **good quality of grape yields**. Existing automatic machines for vineyard pruning perform brute operations on the plants to decrease the cost and time of the process. Moreover, high-quality pruning often relies on specific human expertise, that could change according to the different policies adopted. Thus, a further goal of automatizing this process consists in embedding the human expert knowledge into the robots' commands.

The project "VinPRO: Vineyard Pruning with Robots through Collaborative Learning in Virtual Reality" aims to advance vineyard pruning by **integrating cutting-edge technologies and human knowledge** in an innovative approach.

The key goals of the project consist of:

- Developing an **automatic robot solution** for vineyard pruning operations. The team will start with commercial equipment composed of a robotic arm and sensors and will develop custom end-effector and actuation systems to cut branches.
- Developing a precise **computer vision** pipeline to identify branch node.
- Programming a learning from demonstration paradigm to transfer the knowledge of the **human expert** into a robotic policy.
- Integrating the learning process in a **Virtual Reality** framework to safely train both the robot and the operator on the collaborative task.

A multidisciplinary approach is required to address the mechatronic design of the robotic platform, the pruning task learning and the human-aware development of the Virtual Reality framework for collaborative operation.

The VinPRO project is expected to bring several benefits:

- *Efficiency*: by automating the pruning process, VinPRO can significantly increase the speed and efficiency of vineyard maintenance.
- *Precision*: computer vision and robotic manipulation ensure precise pruning, which can improve the health and yield of the vines.
- *Reduced labor*: the automation of pruning tasks reduces the need for manual labor, which can be particularly beneficial in regions with labor shortages.
- *Knowledge transfer*: the integration of human-expert knowledge into the robotic decision-making policy allows for the transfer and preservation of skilled pruning techniques.
- *Training and learning*: the use of Virtual Reality for training operators and robots can enhance the learning process, making it more interactive and effective.
- *Sustainability*: VinPRO can contribute to sustainable farming practices, which are increasingly important in the context of climate change and environmental preservation.

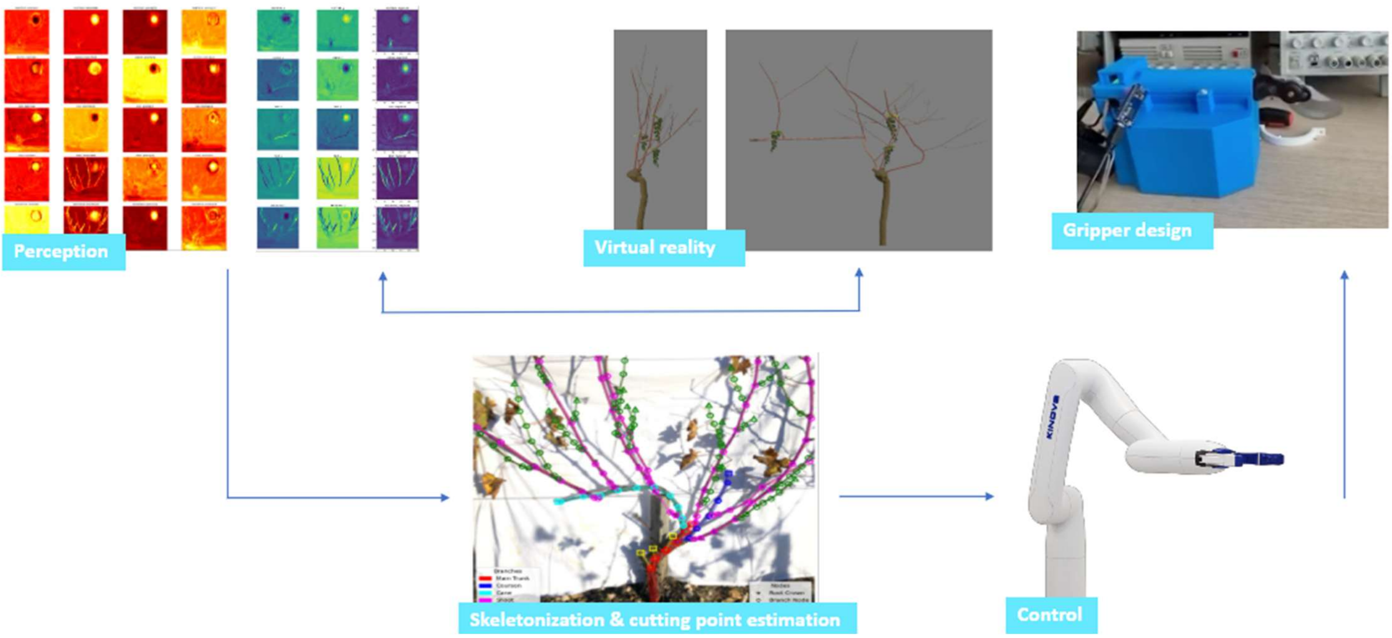

Figure 2: Workflow of the VinPRO robotic vineyard pruning system.

Team description by skill

The project was carried out by an interdisciplinary team that divided the work into four main Work Packages (WPs), each assigned to a subgroup of members according to their background and expertise. This structure ensured that all critical aspects of the VinPRO system were addressed in parallel, while regular meetings allowed the groups to align results between perception, mechanics, control, and simulation.

- **WP1**: composed of Eleonora Troilo, Riccardo Vallino, and Lorenzo Vignoli, all Mechanical and Aerospace Engineers. The group was responsible for the design and realization of the pruning end effector. Their work began with the development and evaluation of different actuation options, including pneumatic and electric solutions, finally choosing the latter. The team realized the full actuation system, 3D-printed the components, and carried out the final validation to confirm the system's performance.

- **WP2**: composed of Vincenzo Avantaggiato and Alberto Eusebio, both Computer Engineers. The group was responsible for the computer vision pipeline, the "eyes" of the robot. Their work focused on detecting branches and nodes with a deep-learning pipeline capable of analyzing complex vine structures. Their work involved iterative training and optimization of neural models to evaluate optimal cutting points directly from image data.

- **WP3**: composed of Riccardo Ghianni and Faik Tahirović, respectively a Quantum and an Automation Engineer. The group was responsible for translating perception outputs into concrete robotic actions. Their task was to design a control system that receives the cutting points and generates feasible trajectories to avoid collisions.

- **WP4**: composed of Francesco Risso, a Computer Engineer in charge of developing a virtual vineyard environment in Unity, fully integrated with ROS2. His work provided a risk-free testing ground that realistically simulates vine growth, leaf orientation, and branching patterns, allowing the team to model interactions between the robotic system and the operator.

The team successfully collaborated with PIC4SeR (Turin). All Work Packages worked at the center to 3D-print components, test algorithms, and integrate the outputs of the different groups. PIC4SeR also provided access to advanced robotic equipment that was integrated into the system. Finally, a field trip to the Cantina 366 vineyard in Agliè (TO) allowed the team to confront real environmental conditions.

Goal

The goal of Team VinPRO is to design a robotic solution that automates the most labor-intensive aspects of vineyard pruning. The system should be adaptable to diverse terrains and vineyard layouts, capable of delivering a **high throughput of pruned vines** while maintaining precision. To ensure adoption, the solution must remain cost-effective without compromising accuracy.

Achieving this requires several key developments: the ability to recognize **vine structures**, identify optimal **cutting points**, and reliably **execute cuts** with a robotic manipulator. A custom cutting tool must be designed for consistent performance in varied conditions, while virtual simulations provide a platform to integrate expert knowledge and improve decision-making.

Key objectives include:

- Design and integration of cutting tools: selecting an efficient **actuator** and building custom cutters that deliver accurate performance at low cost.

- Branch and **cut-point recognition**: developing algorithms capable of detecting vine branches and determining precise cutting nodes.

- **Path planning** and manipulator control: implementing motion strategies that allow the robot to reach each cutting point while safely avoiding obstacles.

- **Virtual vineyard** development: creating an interactive environment where expert pruners' knowledge can be captured and translated into training data for the model.

Understanding the problem

Pruning is a fundamental part of viticulture, shaping vine growth and directly influencing grape yield and wine quality. Yet, the sector is facing a critical challenge: the number of **skilled workers** capable of carrying out this labor-intensive process is steadily declining. The workforce is aging, and fewer young people are entering agricultural labor.

Italy remains the **world's largest wine producer**, responsible for nearly 49.8 million hectoliters of wine in 2022—around 19% of global production. However, vineyard labor is under increasing strain. Between 2010 and 2020, the number of wineries in Italy fell by one-third, leaving fewer operators responsible for larger plots of land, while the majority of workers are growing older. Without new solutions, labor shortages threaten both productivity and quality in wine production.

The conditions under which pruning takes place make matters even more complex. Vineyards are often located on steep slopes, uneven terrain, and narrow rows, requiring flexibility and precision from workers. Pruning is usually performed in the coldest months of the year—January and February—when low temperatures, rain, and snow add to the difficulty. These factors not only increase the physical demands of the task but also **complicate the design** of any automated solution.

Economic sustainability is another pressing concern. Manual pruning is costly, accounting for up to a quarter of annual labor expenses in fruit production. At the same time, vineyard businesses operate in **seasonal cycles**, with irregular income and long return-on-investment horizons.

For many small and medium producers, investing in advanced machinery is a financial risk that may take several harvests to balance out. Any automation technology must therefore be not only reliable in challenging conditions but also **affordable and accessible**, ensuring that growers can adopt it without compromising their economic stability.

Exploring the opportunities

Competitor analysis revealed that **no existing solution** offers vineyard owners a truly universal system — one that adapts to diverse terrains and vineyard layouts while integrating the expertise of human pruners.

Companies such as BFM, Orizzonti, and Vision Robotics provide mechanized solutions, but these systems are prohibitively expensive, require significant vineyard modifications, and are aimed primarily at large-scale operations. Even emerging technologies, such as Atria, remain **limited in scope** and do not provide the flexibility needed for widespread adoption.

Discussions with **vineyard owners**, such as Francesco from Cantina 366, highlight this gap. He emphasized that current solutions fail to keep production costs manageable. For small businesses selling wine at around €4 per liter, the high cost of machinery — combined with the need to restructure vineyards to fit the equipment — makes such investments unrealistic.

This creates a clear opportunity for a solution designed with small and medium-sized producers in mind. A smaller, **more adaptable robotic system** would reduce dependency on large tractors and flat terrain, allowing vines to be planted more densely and improving overall efficiency.

Compact **autonomous vehicles** already exist that are capable of navigating steep, uneven ground. By equipping them with intelligent pruning capabilities, it becomes possible to deliver a cost-effective, versatile solution that preserves expert knowledge, supports productivity, and remains accessible to growers across vineyard scales.

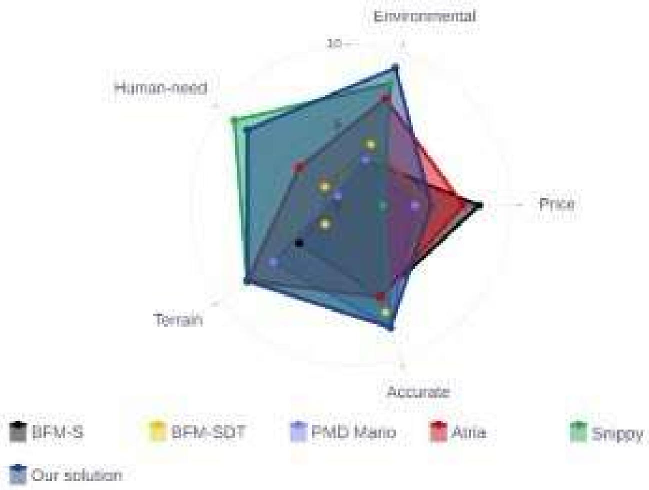

Figure 3: Competitor analysis of vineyard pruning solutions.

Generating a solution

Our proposed solution combines a Kinova Gen3 Lite **6-DOF robotic manipulator** with a mobile autonomous vehicle (AV). This setup keeps costs low while ensuring high mobility across diverse terrains and vineyard environments. The manipulator provides precise control over pruning actions, while the AV enables access even in challenging vineyard layouts.

Perception and planning are achieved through an **integrated vision system**: an Intel RealSense D435i depth camera and a LiDAR sensor map the environment, detecting both vines and obstacles with high accuracy. This dual-sensor approach provides a detailed three-dimensional understanding of the scene, ensuring reliable operations.

These inputs feed into a **motion-planning algorithm** built in ROS 2 Humble with the MoveIt Task Constructor, which calculates collision-free paths to the cutting points. This software layer translates raw perception data into safe and smooth arm movements that respect both the geometry of the vine and the robot's kinematic constraints.

Cutting points are identified by a custom **deep learning** model. The model locates key nodes on each vine, determines optimal cuts in image space, and converts them into real-world coordinates through triangulation. By learning from expert pruning practices, the model is able to preserve viticulture knowledge and apply it to the plants.

Once the manipulator aligns with a cutting point, a **custom electrical actuator** — controlled by a dedicated Arduino board — triggers the pruning tool. Unlike pneumatic systems, the electrical design minimizes maintenance costs while ensuring high precision. The housing for the actuator was 3D printed at PIC4SeR (Turin) to allow lightweight integration with the manipulator's gripper.

To validate the system, we developed a **virtual vineyard** in Unity with full ROS 2 integration. This simulation environment realistically models vine growth, gravity-driven leaf orientation, and natural branch structures. It enables safe testing of pruning strategies and offers the potential to train improved cutting policies based on expert demonstrations in the interactive scene.

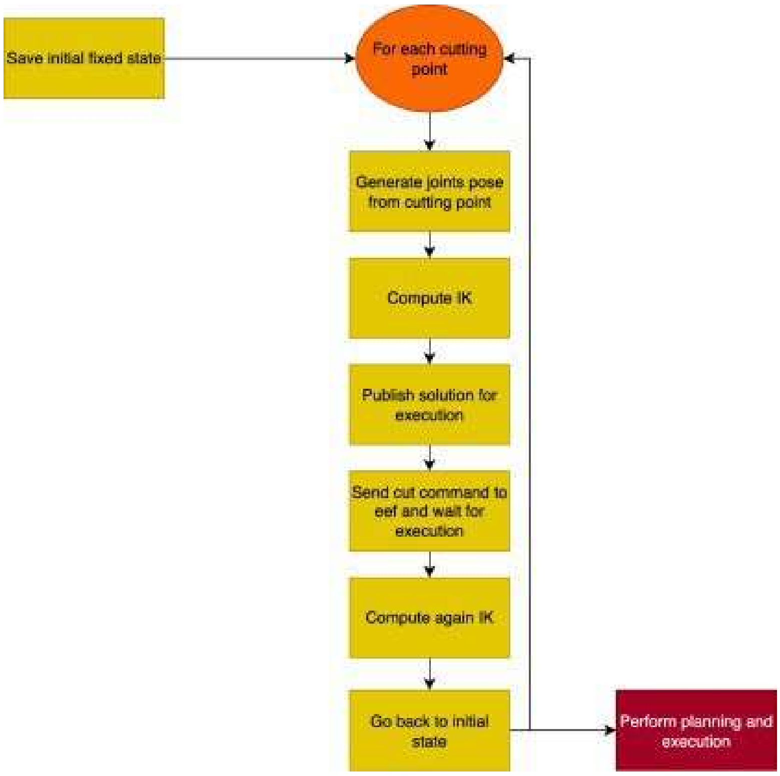

Figure 4: Flowchart of the motion planning and execution pipeline

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