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The forest lift
─ A rugged tool to simplify pruning and fruit collection ─

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Abstract

Extreme environments, like the steep olive groves in Liguria, Italy, cannot be reached by tractors and large-sized devices. This paper describes a small, tracked elevation platform able to lift the farmers close to the branches for harvesting or pruning. The vehicle moves thanks to tracks. The elevation platform, having no motors and no sensors, is powered by hand. A prototype of the forest lift has been tested on the field. The forest lift has a maximum elevation of 2 m with a tilting (0° + 30°) and rolling mechanism (−15° + 15°) compensating for steep terrains. The iron prototype weighs 400 kg and is 3,160 mm tall, 2,000 mm long and 900 mm wide.

[Keywords] elevated platform, green automation, passive actuation, olive harvesting, agriculture machinery, safety device

1. Introduction

Nowadays, agriculture is intensively done on flat terrains where heavy machinery can be adopted for seeding, pruning and harvesting (Rose et al., 2021; Zhou et al. 2022). Nevertheless, many rural areas have an uneven conformation of the terrain. There is a crisis in hill agriculture. Water scarcity and restricted croplands are problems for these marginal lands. These challenging circumstances inhibit entrepreneurship. Non-palatable invasive species infest many areas. Overall, the limited sustainability of hill agriculture creates urbanism and expansion of uncultivated land (Partap, 2011). Agricultural operations in these regions are frequently done by hand, with limited or absent support of machines. Frugal exoskeletons may be adopted to simplify fruit collection (Reverberi et al, 2023). This intense human labour has a direct impact on farmers health (Davis et al., 2007; Osborne et al., 2012; Fulmer et al., 2002) and food prices. Another side effect of agriculture on arduous lands is the high number of accidents: farmers and foresters normally use ladders or climb directly onto trees (Van Der Windt et al., 2000; Thamsuwan et al., 2019). Falling from a tree or a terrace may cause spinal injury or fatal accidents (Faergemann et al., 2001). While the project is focused on olive tree production, similar scenarios are present in every situation where there is fruit production from trees growing on uneven terrain.

The construction industry may also profitably use the forest lift (Moriguchi et al., 2013; Dasgupta et al., 2014). The rise in the population's age and the increased costs of hand labour tend to limit the development of agriculture in these regions, consequently limiting the market of high-quality products. The objective of this research is to create a device that can support farmers in elevation work on uneven terrains (Cepolina et al, 2024).

2. Materials and methods

2.1. The working place

It is crucial to fully assess the characteristics of the "working area" to create a suitable sensor fusion and a correct machine interaction (Masood et al., 2020). There is a rich state-of-the-art related to autonomous vehicles (Bergerman et al., 2015); autonomous machines can be used for intelligent manufacturing city transport (Cepolina et al., 2021) and harvesting (Vásconez et al., 2022; Rose, 2023). Examples of powered ladders in agriculture also exist (Pegna, 2008; Pathaveerat et al., 1993). First, the machine must be positioned in the desired position, and then the operator can climb close to the tree branches for pruning and harvesting operations (Thamsuwan et al., 2020a; Thamsuwan et al., 2020b). Thanks to the evolution of robotics (Molfino et al., 2023), fully autonomous and remote-controlled self-levelling platforms are available on the market (Cepolina et al., 2022; Sotnik et al., 2022). Hybrid robotic systems can be used for harvesting (Kim et al., 2008). Robots are transforming the work on farm (Martin et al., 2022; Zhang et al. 2019): work-related impacts (Baur et al., 2023) and ethical aspects (Sparrow et al. 2021; Daum, 2021) must be considered. Harvesting An automated mini-scissor self-levelling crawled platform (Bibi 850-BL, ALMAC S.p.A., Italy) costs around 20.000 €: the load capacity is 250 kg and can reach 7.9 m in height. The length, width and height are 1,940, 1,300 and 2,500 mm, respectively.

2.2. The working conditions

The device, the object of the study, is designed to work outdoors in Liguria lands, where the configuration of the soil can vary from ordered terraces to irregular land. The terraces where olive trees grow are reached by narrow paths full of obstacles, such as large stones. The air is rich in sea salt, while

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stormy winds and rain are common. Sensors, motors and control algorithms may be spoiled by humidity or dust. Maintenance is not always an option outdoors. Safety is a primary need; the positioning of the platform must be fast and user-friendly.

2.3. The virtual environment

The device under study shall satisfy two needs: agility to move along rough terrains and comfort in usage. To verify the machine and environment interaction and the machine and human interface, a virtual environment is created where different mannequins conduct agriculture activities. This environment is used to quickly evaluate possible architectures that can guarantee safety and easiness of use (Miles et al., 1996). A selection of the preferred mechanical designs is now described. For each solution, the advantages and the drawbacks are underlined.

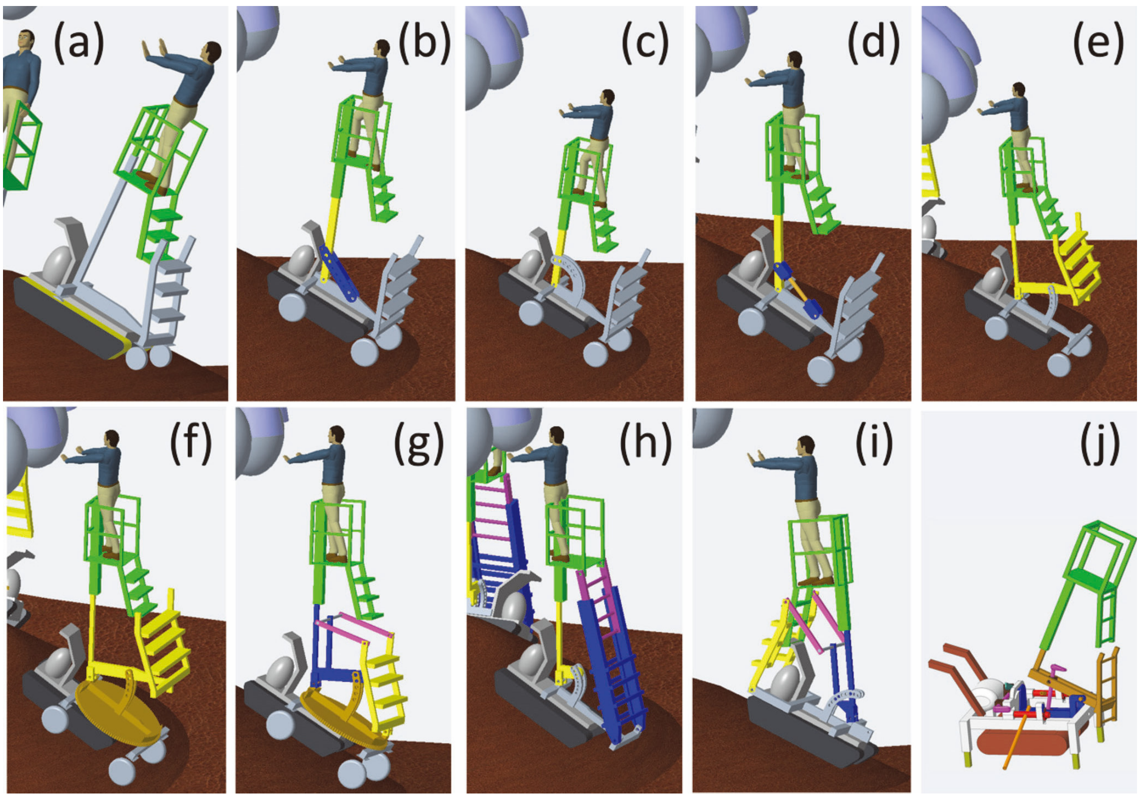
2.4. The machines union

To simplify the project, we chose to displace a commercial platform (Quickstep 200, Laing Access Platforms Ltd., UK) using a commercial tracked mini dumper (GKZ 500 H, Dotor Trator s.n.c., Italy). The overall design is faster, and the acquisition of spare parts is simplified. Many farmers already own mini dumpers; this modular approach may also lower the cost of the system, having the possibility to commercialise the "add-on" ladder only. The tracked vehicle may tow a wheeled ladder; however, this "train" solution has been rejected due to manoeuvrability concerns. A more compact solution has been searched for. The tracked vehicle, without the loading bed, is positioned under a ladder; a physical interface firmly links the two elements (Fig. 1 (a)). This solution minimises the overall length of the device. A passive mechanism powered by an air spring adjusts the vertical position of the platform. Once the ladder is positioned under the tree, the air spring can raise the cage to its uttermost position. Next, a lock mechanism secures the cage in this position. Once the operator reaches the cage by climbing onto the ladder, operator uses operator's weight to lower the cage by simply operating the locking lever. This mechanism, without the need for a motor, can lower the platform to the desired height.

2.4.1. The tilting ladders

For comfort and safety reasons, the platform needs to be horizontal (Elkins et al., 2010). A tilting mechanism can compensate for the terrain slope. The upper part of the ladder can be pitched with a locking pin mechanism (Fig. 1 (b)); the sets of holes, for the angle regulation, may also be disposed along an arc (Fig. 1 (c)). For a finer adjustment, the pin and hole mechanism can be replaced using a nut and screw (Fig. 1 (d)).

The solution provided a tilt-only in the upper steps of the stairs, while the lower steps were firmly joined to the tracked



(a) joined machines, (b) tilting ladder: linear locking pin join, (c) tilting ladder: arc locking pin join, (d) tilting ladder: nut/screw join, (e) tilting ladder: overall rise, (f) tilt and roll ladder: overall rise, (g) tilt and roll ladder: parallelogram mechanism, (h) tilting ladder: extendable ladder, (i) tilting ladder: front climb, (j) tilt and roll ladder: cradle.

Fig. 1 Forest lift models

vehicle. In the case of highly leaning terrains (i.e., for 30 °), the gap between the two sets of steps can be dangerous (Fig. 1 (d)): the user may have problems descending from the device after completing a task. Tilting the overall ladder on a pin linked with the lower machine frame may solve this problem (Fig. 1 (e)). A retractable portion of the ladder may be linked to the lower part of the ladder to simplify the rise and descent.

2.4.2. Tilting ladder on a rolling platform

Sometimes, due to space constraints, it is not possible to fully align the tracks along the slope. To overcome this additional concern, it is possible to place a rolling mechanism under the mentioned tilting mechanism frame (Fig. 1 (f)). This hand-actuated joint has a reasonable range of action to adapt to the slopes. The benefits of this rolling platform come at a cost: this machine has additional complexity, weight and cost compared to the other solutions.

2.4.3. Tilting steps

While the upper stairs of the ladder are welded to the working platform, it may be interesting if the lower stair could self-adjust their positions to follow the pole tilt that supports the working platform. A parallelogram may be used for this purpose (Fig. 1 (g)). This elegant solution has the drawback of adding some complexity to the system; the pins of the parallelogram are potential weak spots in a harsh environment.

2.4.4. Extendable ladder

The machine height needs to be limited to move under the branches of the trees. A flexible rope ladder may contribute to reducing the machine's height. This type of ladder, if not well-tensioned, may offer limited stability. A rigid extendable ladder could solve the problem (Fig. 1 (h)). The ladder is formed by two parts: the internal upper ladder slides inside the lower larger ladder. When the platform is fully down, the ladder is very compact. The design of the machine needs to be performed with care; pebbles and sand shall not interfere with the ladder's retractable mechanism.

2.4.5. Front climb

The farmer drives his tracked vehicle from behind, i.e., he walks and controls the vehicle positioned in front of him. Sometimes, the landscape is so rough that the farmer cannot access the back of the vehicle. To solve this problem, the ladder may be rotated 180 °. In this case, the lower part of the ladder is split into two parts: on the left and the right of the heat engine that powers the tracks (Fig. 1 (i)).

2.4.6. Cradle

The ladder with the cradle mechanism is the final evolution of this series of cradle lifts (Fig. 1 (j)). This mechanism, developed in collaboration with the Laing Access company, is a sort of spherical joint. On the base frame (Fig. 2 (a)) can rotate a cradle (Fig. 2 (b)); a screw mechanism allows this movement (Fig. 2 (c)). The cradle brake locks the cradle in position (Fig. 2 (d)). The upper ladder frame (Fig. 2 (e)) can tilt with respect to the cradle; a screw controls the upper frame tilt (Fig. 2 (f)). The cradle mechanism can compensate, using tilt and roll, for different slopes (Fig. 3).

2.5. Comparison of forest lift models

Each of the proposed forest lift models has peculiar characteristics, optimal for a specific mission. Six key performance

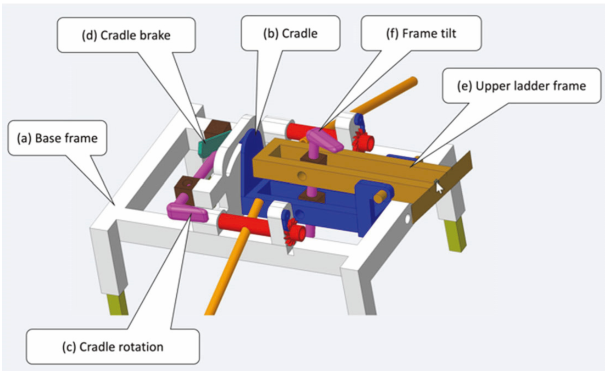


Fig. 2 Detail of the cradle mechanism

Fig. 3 Different orientations of the ladder with the cradle mechanism

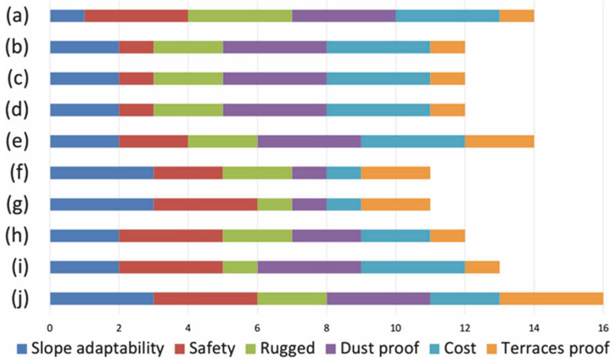


Fig. 4 Comparison of forest lift models

indicators (KPI) have been introduced to compare the models (Fig. 4). Each KPI ranges between 1 and 3 (low to high). "Slope adaptability" relates to the DoFs of the forest lift. "Safety" judges how easy the ladder is to climb. "Rugged" shows the resistance against accidental impacts. "Dust proof" equipment effectively operates in the presence of mud or dust. "Cost" represents an estimation of the cost to create the forest lift. Finally, "Terrace proof" is a KPI related specifically to the capability to work efficiently on terraced fields. The model "(a) joined machines joined machines" is a safe, minimal, rugged and cheap solution that is perfect for almost flat regions, while the model "(j) cradle" is a compromise between agility, robustness and the costs for rough terrains. The cradle model has been selected because its characteristics best fit the Liguria extreme environment.

2.6. Constraint analysis

A simple kinematic analysis of the cradle platform is performed to precisely assess the positioning of the kinematic components involved. The general constraint analysis is completed using the screw theory. The following step includes a dynamic analysis using a partial differentiation method with Denavit-Hartemberg parameterisation. We identify a standard basis for a particular Cartesian frame in space with the six-dimensional space of twists, and the dual basis with the dual space of wrenches with coordinates of twist $\xi = (\omega, v)$, of wrench $\zeta = (f, m)$ and "o" the reciprocal screw product. For the kinematic chain k, joint screws W_k and non-actuated screws V_k span the twist system T_k and its perpendicular complement P_k. The motion of the device can be described by a combination of these screws.

$$W_k = T_k^{\perp} \tag{1}$$

$$V_k = P_k^{\perp} \tag{2}$$

The equations (1) and (2) correlate these screws and the twist system. The symbol "⊥" denotes the orthogonal complement, meaning that W_k and V_k are perpendicular to T_k and P_k, respectively. The twist system T_k is the full set of twists of the mechanism k. The twist system P_k is the set of twists of the actuated joints of the mechanism k. The space W_k represents the structural constraints generated by the geometry of the links that constitute the kinematic chain: the wrenches are reciprocal to all the joint screws that the kinematic chain can transmit when all its joints are left to move freely. The space V_k represents the wrenches that the kinematic chain k can transmit when the actuated joints are locked; the actuated constraints are the set of wrenches in reciprocal to the passive joint screws.

Table 1 Motion, constraint, and reciprocity rule

Motion	Constraint	Reciprocity
Rotation	Force	Coplanar axes
Translation	Torque	Always
Rotation	Torque	Perpendicular
Translation	Force	Perpendicular

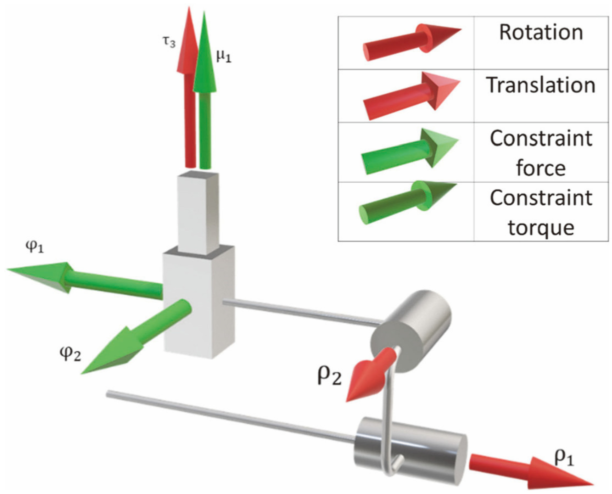


Fig. 5 Constraint analysis

Given these assumptions, a geometric approach to applying the reciprocity rule can be applied using Table 1. The geometric method employed is displayed in Fig. 5. By applying such notation on the kinematic chain of the prototype to be developed, a possible result is the following.

$$\dim(T_1) = 3 \tag{3}$$

$$\dim(W_1) = 3 \tag{4}$$

$$\mathrm{Span}(T_1) = \rho_1, \rho_2, \tau_3 \tag{5}$$

$$\mathrm{Span}(W_1) = \varphi_1, \varphi_2, \mu_1 \tag{6}$$

The kinematic chain structural constraints are below.

- The wrenches φ_1, φ_2 (force) coplanar to twists ρ_1 and ρ_2 (rotations) and perpendicular to τ_3 (translation).
- The wrench μ_1 (torque) orthogonal to ρ_1, ρ_2 (rotations).

2.7. Dynamic analysis

Considering the Denavit-Hartenberg parametrisation displayed below, the goal is to obtain the Jacobian matrix that relates the velocity of the joints with respect to the velocity of the end effector (Fig. 6).

O_n is the origin of the coordinate system. The parameters shown are:

- a_n link length: distance between Z_n and Z_{n-1} axis
- d_n link offset: distance of O_n with respect to O_{n-1} on the Z_{n-1} axis
- θ_n joint angle: rotation around Z_{n-1} axis

To describe a change in the coordinates of one reference frame with respect to the previous, both the translational and the rotational components of motion must be considered. These components can easily be extrapolated from the geometry of the kinematic chain. Consequently below is the transformation matrix from one reference frame with respect to the previous one.

$$T_n^{n-1} = (R_n^{n-1}\ d_n^{n-1}\ \ 0\ 0\ 0\ 1) \qquad (7)$$

Pre-multiplying each transformation matrix for all the previous ones, the transformation matrix with respect to the base frame is obtained.

$$T_i^0 = T_1^0 * T_2^1 *\ldots* T_i^{i-1} *\ldots* T_n^{n-1} \qquad (8)$$

The components of such matrix are below.

$$T_n^0 = (R_n^0\ d_n^0\ \ 0\ 0\ 0\ 1) \qquad (9)$$

Each element of the Jacobian matrix can be computed using Table 2.

ζ_e is a wrench vector whose components represent the forces and torques that need to be applied at every actuated joint to maintain the kinematic chain balanced. Φ is the resulting vector when the wrench ζ_e is multiplied by the transpose of the Jacobian matrix J'.

$$\Phi = J'\zeta_e \qquad (10)$$

2.8. Dimensioning and FEM

Once the loads are on the actuated joints, the dimensioning of the metallic components is performed. As stated before, the preferable material for the embedment of the platform and the tracked vehicle is the same as the one used to build the platform in the first place. Although the mechanism has a simple structure, to fully assess the disposition and magnitude of stress involved, a finite element simulation is employed that uses the Von Mises criterion. Considering an overall load of the platform of 5,000 N and a safety factor of 5 iterating on the 3D model, the design can be optimised and engineered (Fig. 7).

2.9. On field tests

A campaign of indoor and outdoor tests has been performed on the prototype. The objective of the tests is to assess the performance and working limits of the forest lift.

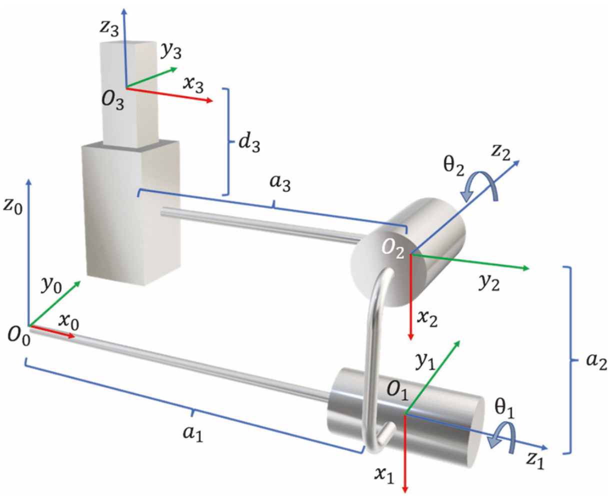


Fig. 6 Denavit-Hartenberg parametrization

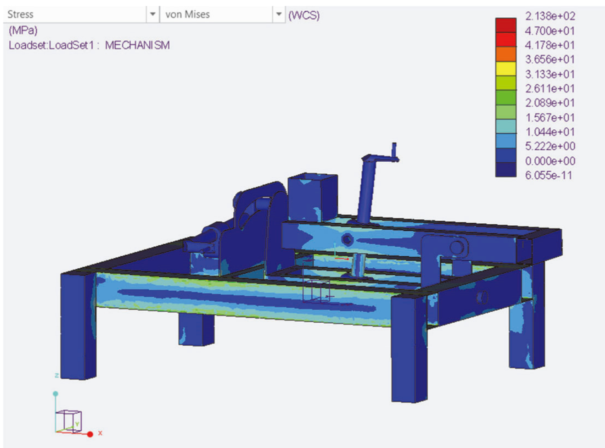


Fig. 7 Finite element model

Table 2 Jacobian matrix elements

	prismatic	revolute	cylindrical
linear	$R_{i-1}^0 \begin{pmatrix}0\\0\\1\end{pmatrix}$	$R_{i-1}^0 \begin{pmatrix}0\\0\\1\end{pmatrix} X(d_n^0 - d_{i-1}^0)$	$R_{i-1}^0 \begin{pmatrix}0\\0\\1\end{pmatrix} + R_{i-1}^0 \begin{pmatrix}0\\0\\1\end{pmatrix} X(d_n^0 - d_{i-1}^0)$
rotational	$\begin{pmatrix}0\\0\\0\end{pmatrix}$	$R_{i-1}^0 \begin{pmatrix}0\\0\\1\end{pmatrix}$	$R_{i-1}^0 \begin{pmatrix}0\\0\\1\end{pmatrix}$

Test 1: The ladder is set up in its compact form. An operator drives the machine indoors on a 25° tilt ramp. The motion is repeated 5 times. The wood ramp is clean, and the concrete surface is dry—perfect conditions.

Test 2: The forest lift is operated in its compact shape, outdoors on a hill inside a forest. There is mud and grass on the moist landscape. The hillside path features gradients ranging from −45° to +45°, which are difficult conditions.

Test 3: Overall, 15 farmers have been invited to test the forest lift on the fields of Liguria. Most of the farmers are males, the average age is 43 years. The farmers manoeuvre the forest lift along the terraces. The side stabilisers are positioned. The lift is levelled using the cradle tilt and roll and then extended. The farmers, standing on the platform, mimic trimming tasks using a telescopic handsaw.

3. Results and discussion

3.1. Evaluation of the virtual prototypes

Overall, 10 virtual prototypes of the agricultural platforms have been developed. All the models originate from the fusion of a tracked vehicle and a tilting ladder. To enhance the machine's dexterity and stability, the tracked vehicle, and the ladder overlap. The wheeled vehicles can easily rotate in place. The connection between the mini-dumper and the platform is obtained using the same pin connections to secure the cargo box. With such a strategy, the mini dumper's overall structure is not permanently modified, and a rollback on the previous commercial setup can be easily performed. For flat terrains, the vehicle and the ladder can be directly joined (Fig. 1 (a)). To compensate for irregular terrains, one DoF joint (Fig. 1 (b), (c), (d), (e), (h), (i)) and two DoFs joints (Fig. 1 (f), (g), (j)) are proposed. The farmer, to reach the working platform, needs to climb onto a ladder; different solutions have been proposed to make steps easy and safe to climb. Both the climb from the front and the back of the machine have been considered. The cradle lift is the preferred forest lift model. The kinematic analysis of the cradle lift has been performed to evaluate the platform workspace. The dynamic analysis of the mechanism has also been introduced. A finite element simulation allowed us to optimise the size of the machine.

3.2. Full-scale prototype

A full-scale prototype of the forest lift has been created (Figs. 8 and 9). For agricultural use, the forest lift must be robust. The potential customers have a limited budget: the target price of the full equipment (dumper and ladder) is under 6,000 €. The machine is painted iron due to cost and usability considerations. Glass Fiber Reinforced Polymer (GFRP) has also been evaluated as a possible alternative lighter solution (Cepolina et al, 2023). The prototype weighs 400 kg and is 3,160 mm tall, 2,000 mm long and 900 mm wide. Locomotion is powered by a 196 cm³ petrol engine (GX 200, Honda Motor Co., Ltd., Japan),

Fig. 8 Ladder prototype

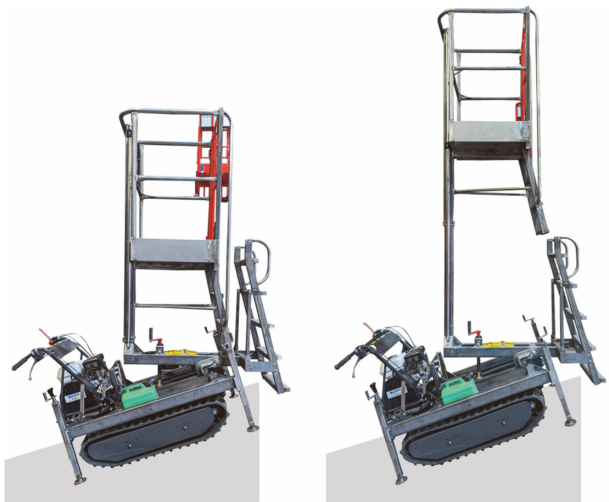


Fig. 9 Ladder prototype on a slope in the retracted and extended positions

having a maximum power of 4.3 kW. The transmission is mechanical; there are 3 forward gears and 1 reverse gear. The measured tilt range (0° + 30°) and roll range (−15° + 15°) can compensate for a wide range of steep terrains (Fig. 8). The commercial tracked mini dumper (GKZ 500 H) is rated to climb on a maximum slope of 40° without load. In case of load, the maximum slope is 20°. Under the "forest lift" configuration, the mini dumper carries the commercial platform (Quickstep 200). The forest lift maximum slope is between 20° and 40°.

Fig. 10 Forest lift on field tests inside a terraced olive grove

The maximum platform elevation is below 2 m because Italian law (art. 107 of the Legislative Decree 81/08) states that operators working above 2 m in height must use safety equipment (Longo et al., 2013). A patent application has been filed to protect the rights to the machine.

3.3. Test results

Test 1: The results of test 1 show that the forest lift can stay on a 25° dry slope without slipping. The forest lift moves across this slope with ease. The tracked vehicle, while moving, is not slipping with respect to the ground. The ladder restricts the operator's view, making it difficult for him to look forward.

Test 2: The tracked wheel offers a perfect grip on rough concrete while it tends to slip on muddy soil. The tracks, on the soil, tend to slide on slopes higher than 30° (and lower than −30°). To increase track friction, the operator climbs onto the first step of the ladder. Even in its small form, the vehicle is quite tall and is unable to manoeuvre beneath trees with short branches. To avoid hazardous situations, the operator must always choose smooth paths. According to the soil condition, the forest lift changes highly its behaviour: the device cannot be used on very slippery ground.

Test 3: Test 3 has been performed on an olive grove with terraces (Fig. 10). The results of test 3 are reported (Fig. 11). The scale of the rating ranges between 0 and 10 (low to high). The tracked vehicle drive dexterity is perceived as adequate (average score 6.6/10, standard deviation 0.806). The levelling easiness is good (average score 6.8/10, standard deviation 1.032). The stability of the forest lift is far higher than that of a typical ladder (average score 7.3/10, standard deviation 1.033). The operator, being inside the platform cage, can lean both

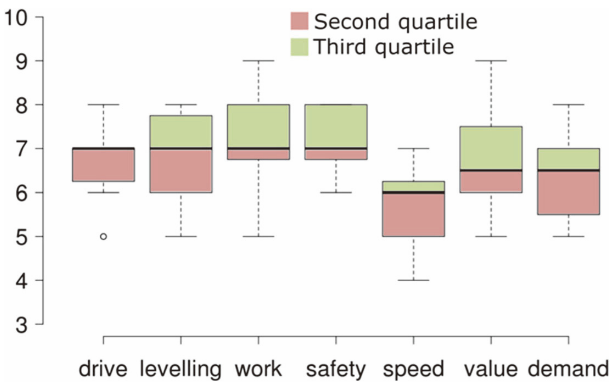


Fig. 11 Evaluation of the forest lift prototype

arms out of the cage without fear of falling. The platform also allows to work safely (average score 7.2/10, standard deviation 0.678). The equipment is simple to use, but many farmers are dissatisfied with the slow setup (average score 5.6/10, standard deviation 0.998): it takes 4 minutes for complete stabilisation and levelling. The platform seems to be cheap for the value proposed (average score 6.9/10, standard deviation 1.172). The willingness to buy the device is still limited (average score 6.3/10, standard deviation 0.996). The overall feedback, given by the users, is encouraging. The prototype created is robust, easy, and safe to operate. However, the slowness of positioning makes the device unattractive for the farmers who need to reposition the "ladder" very frequently.

4. Conclusions

This paper described a tracked semi-automated elevation platform suitable for agricultural activities, mainly for trees grown on steep terrains. It is challenging to design an easy-to-use ladder that requires low maintenance and guarantees a high level of safety. Several solutions have been evaluated and compared. The winning model has been prototyped and tested out in the field. The results have been promising. In the following months, new prototypes will be created following precious feedback from the end users who have tested the new equipment. The possibility of the tracked elevation platform becoming a compulsory piece of safety equipment is under evaluation.

Acknowledgements

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