Article

Design and Lateral Stability Analysis of an Attitude Adjustment Tractor for Moving on Side Slopes

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Abstract: Lateral overturns are the most frequent fatal accidents involving tractors. A tractor being able to travel safely on uneven or sloped terrain is still an open field of investigation. The design concept of a four-wheel-drive tractor that can traverse hilly and mountainous areas is described. The tractor's locomotion system can actively adjust its roll angle by using the attitude adjustment mechanisms equipped on the rear wheels. With double quadrangle mechanisms, the front axle can cooperate with the rear axle to adjust this tractor's attitude. This tractor can also level its body, steer, and transmit power. The principles and configurations of the two axles are presented. A mathematics/mechanical model of a tractor on lateral slopes was developed. This model considers the relationships of the ground supporting forces when the tractor adjusts its roll angle. Combining the model of specific attitude adjustment mechanisms and the above mechanics model, the lateral stability analysis associated with the active input of the attitude adjustment mechanism is conducted. The reliability of the proposed model is discussed based on a comparison of slope traversing experiments and numerical simulations. This designed tractor has potential application in the fields of hilly and mountainous terrains. The results show that posture/configuration adjustment is a positive way to enhance tractor lateral overturn stability.

Keywords: tractor; stability; modeling; attitude adjustment

1. Introduction

Tractors, known for their multitasking capacity, are widely used in many different farm situations [1]. In particular, tractor overturn accidents account for more than half of all tractor-related deaths [2,3]. It is no wonder that sideways overturning, or lateral rollover, accounts for the majority of overturning injuries [4,5].

A considerable amount of research has been devoted to tractor lateral stability, which can be divided into passive safety prevention and active safety protection [6,7]. The rollover protection structure (ROPS), as a kind of passive way, has been one of the most important advances in protecting the driver from tractor overturn accidents. In addition, ROPS do nothing to prevent accidents, they only reduce the likelihood of serious injury [8]. By contrast, mainstream research on active safety prevention seeks to establish static/quasi-static/dynamic models to reveal the behavior of tractors on different terrains [1,3–11]. Based on these models, tractor stability indicators are able to evaluate the stability of the tractor. However, these results (tractor speed, slope angle, etc.) can only provide some warning to tractors [12,13]. Thus, a locomotion system for tractors that is able to maintain stability in various situations (especially side slopes and uneven terrains) is still essential [14,15].

Locomotion systems with attitude adjustment mechanisms can alter their structures and configurations to change the center of mass. These systems can better adapt to various,

complicated and completely unstructured environments [16,17]. Most of these systems are applied for mobile robots, for example, the Sample Return Rover, Scarab, Tri-Star IV, ATHLETE, Workpartner, MAMMOTH, Hylos, and Sherpa [18–26]. They are mostly a hybrid wheel-legged type with many degrees of freedom (DOFs), adding complexity to the control system [26]. In addition, most of such robots are driven by a motor with no transmission systems.

For tractors, several mechanisms for locomotion systems with attitude adjustment functions have been designed and developed [27–32]. As the degrees of active freedoms are independently actuated, they can actively adjust their postures and structures, thereby enhancing their stability and traction. A four-wheeled slope tractor has been described to change its attitude on side slopes. However, it needs additional active control to keep all four wheels in contact with the ground, adding complexity to the control system [27]. Another four-wheeled tractor has been developed to move on transverse slopes; a brachial mechanism to the rear wheels is used to change the height of the wheels, and a linkage system of the front wheels is provided as the passive part to keep wheels in contact with the ground. As it is a rear-wheel-drive vehicle, the driving performance would be affected when compared to the all-wheel-drive ones [28]. Additionally, a hillside tractor with a balance-rocker mechanism is designed to achieve variable ground clearance and variable wheel tread. But the mechanism systems are complicated [29]. The design and testing of a hillside track tractor with a differential pressure device are also investigated [30]. These studies primarily focused on the design, manufacturing, and testing of such locomotion systems. However, the effects of posture change on the stability of such reconfigurable systems were neither considered explicitly nor evaluated. The stability of the tractor may be significantly influenced by posture or configuration. In fact, it has long been established that sideways overturning, or lateral rollover, accounts for the majority of rollover injuries and fatalities [5]. Meanwhile, several studies have found that when the attitude of a locomotion system is controlled, the stability can be enhanced [25,33,34]. Thus, the model representing the relationship between the configuration/posture of a tractor and its lateral stability is highly required to be established.

On the other hand, the design continuity requires that the new locomotion system should inherit the general structure of the previous tractor, and the changes should be as small as possible. To avoid lateral overturns, this work designs a four-wheeled tractor that integrates the advantages of the mechanisms mentioned above. Inspired by the traditional tractor, this one is modified by the rear and front axles, respectively. For the rear axle, equipping the attitude adjustment mechanism composed of a pair of gears on both sides, thereby changing the height on both sides. For the front axle, it can cooperate with the rear axle to actively adjust the tractor's attitude. Additionally, both the rear and front axles transmit power while ensuring that all four wheels can provide power.

This tractor has two modes of locomotion, while the traditional one only has one mode; a new mode of changing the attitude/configuration enables the tractor to work on side slopes. This locomotion system does not require real-time control to keep all wheels in contact with the ground and reduces the complexity of the control system similar to the traditional tractor. It can also adjust its roll angle/configuration when necessary to enhance its stability. Generally, as a four-wheel-drive tractor, it can work on various terrains, especially the side slopes and uneven terrains.

Therefore, taking the tractor's attitude into consideration, a mathematical model of a tractor on lateral slopes is developed. This general model is formulated, describing the relationship between wheel–soil contact forces as a function of overturn parameters. The designed tractor can adjust its roll angle by attitude adjustment mechanisms. Combining the model of specific attitude adjustment mechanisms and a complete tractor model, the lateral stability analysis associated with the active input of the attitude adjustment mechanism is conducted. Meanwhile, the instability indicator of tractor lateral overturns is obtained for an arbitrary configuration with attitude adjustment mechanisms.

Thus, one main contribution of this study is the description of the design concept of a tractor with attitude adjustment mechanisms. Inspired by the traditional tractor, both front and rear axles are modified to achieve the three functions: attitude adjustment, steering, and power transmission. The designed tractor can also level itself when the angle of the lateral slope is less than 15°. Then, a prototype is manufactured, which is the practical contribution of this study. Another main contribution is to formulate a general mathematical model for the tractor while taking the attitude into consideration and to develop the relationship between the input of the adjustment mechanisms and the tractor's lateral stability. Attitude adjustment parameters are also designed. This is the scientific contribution. The approach developed here provides an effective way to avoid lateral overturns, which are fatal to drivers.

In the present paper, the design concept of the tractor is described in more detail. In addition, a mathematical model representing the relationship between the posture/configuration and the tractor's lateral stability is also built, and verification of the model is discussed based on experiments. The remainder of this paper is organized as follows. Section 2 discusses the design concept of the proposed hillside tractor. Section 3 develops the kinematic model of the adjustment mechanism equipped on the rear wheels. In Section 4, the effects of posture change on lateral stability are based on a mathematical model. Section 5 includes case studies and experiments that validate the lateral stability model. Finally, Section 6 concludes and describes the future works of this paper.

2. Design Concept

2.1. The Conventional Agricultural Wheel Tractor

The configuration of a conventional agricultural wheel tractor is shown in Figure 1. A tractor has no suspension and can be considered as having two parts: the front end and the main body [5]. These two parts are connected by a constraining pivot at the geometric center of the front axle, which rotates parallel to the longitudinal plane of the tractor. A passive degree of freedom (DOF) is provided to keep all four wheels in contact with the ground.
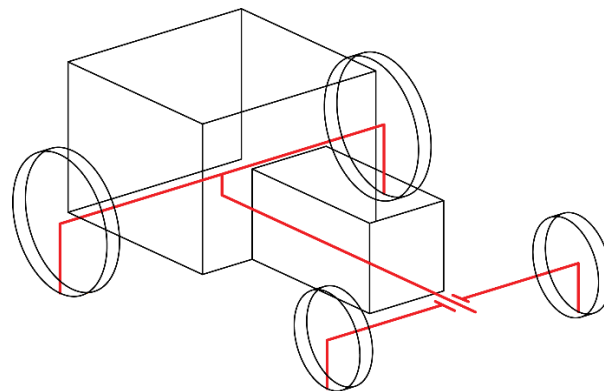

Figure 1. The traditional agricultural tractor.

2.2. A Wheel Tractor with Attitude Adjustment Function

Inspired by the conventional tractor, a modified one is designed to enhance both stability and terrain adaptability. This tractor is modified by rear and front axles, respectively. For the rear axle, by equipping the adjustment mechanism on the rear wheels, the height on each side can be actively adjusted, thereby allowing a change in the tractor's attitude. For the front axle, with the double quadrangle mechanisms, it can cooperate with the rear axle when necessary to adjust the tractor's attitude on slopes with larger angles; it can also make sure there is no interference between attitude adjustment, steering, and power transmission.

2.2.1. Rear Adjustment Drive Axle

The rear adjustment drive axle is shown in Figure 2. As shown in Figure 2a, the rear axle has an axle housing, two slewing bearings, two end driving mechanisms, and two wheels. The entire rear axle is separated by the slewing bearing. The inside of the slewing bearing is mounted to the axle housing, and the outside is fixed connected to the end driving mechanism. The slewing bearing is driven by a hydraulic cylinder, thereby allowing the relative rotation motion between the inside and outside. The front view and left of the rear axle are shown in Figure 2b,c, respectively. As shown in Figure 2e,f, by actively changing the rotation angle (α) of the slewing bearing, the wheel, which is connected to the ending driving mechanism, can rotate around the rotation center of the rear axle. Thereby, the height of each side can be actively adjusted.
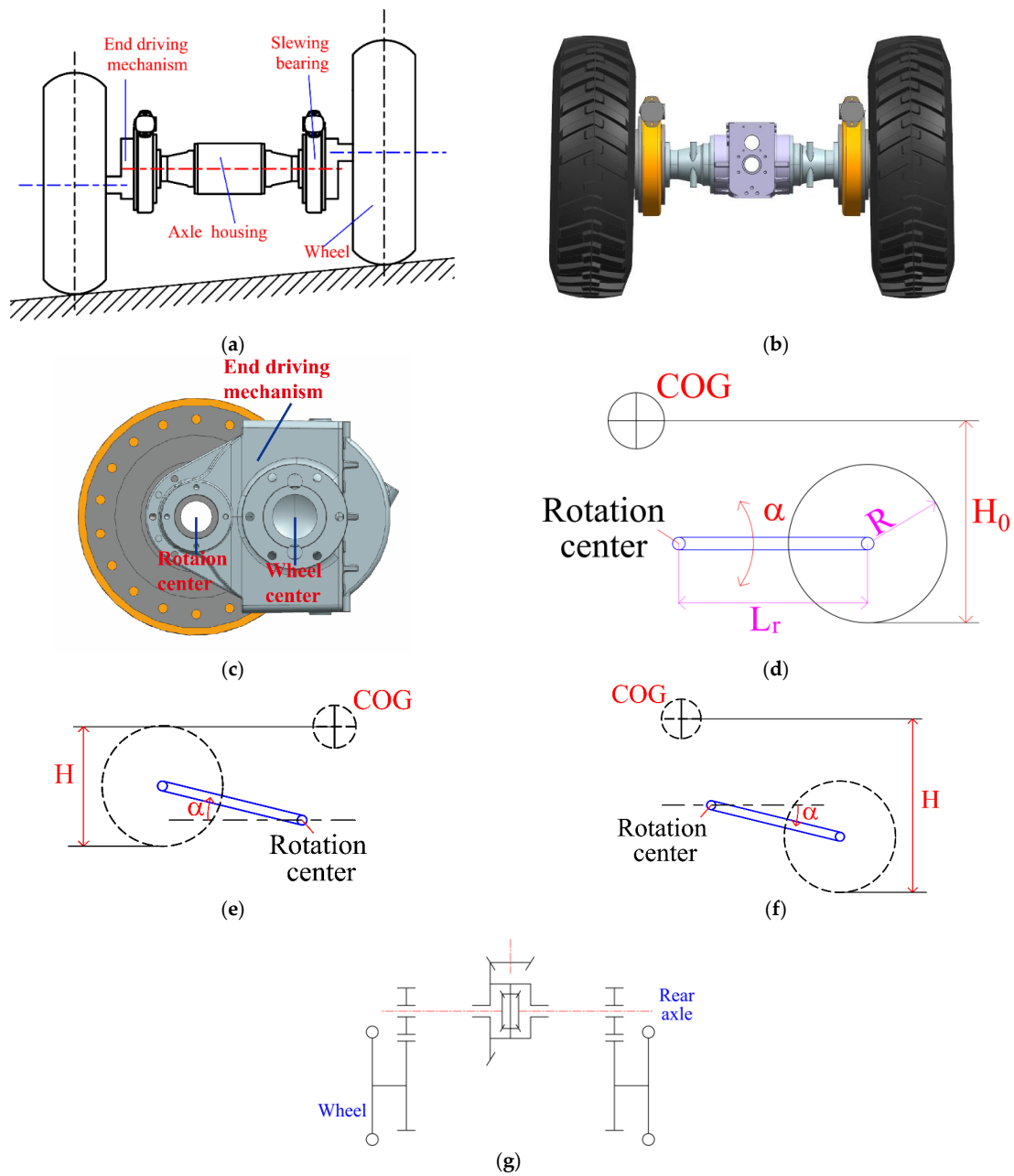

Figure 2. Rear axle: (**a**) Simple model; (**b**) Front view; (**c**) Left view; (**d**) Initial state; (**e**) Turn upward; (**f**) Turn downward; (**g**) Transmission system.

The initial state in Figure 2d. As shown in Figure 2e,f, when the rear wheel rotates upward around the rotation center, the height of COG is reduced; when rotates downward, it is increased. This tractor can adjust its roll angle by changing the height of each side independently. The transmission system is shown in Figure 2g, where the power transfers from the engine to the end driving mechanism through a main reducer and a differential mechanism. Then, power is transferred to the rear wheel by a pair of gears.

Consequently, by changing the rotation angle of the slewing bearing on both sides, the heights of COG on both sides change together. Thus, the attitude of the tractor can be actively adjusted while providing power to the rear wheels.

2.2.2. Front Axle

For a tractor to adjust its attitude, the front axle should have the ability to coordinate with the rear axle. As shown in Figure 3, a new front axle for the hillside tractor is proposed.
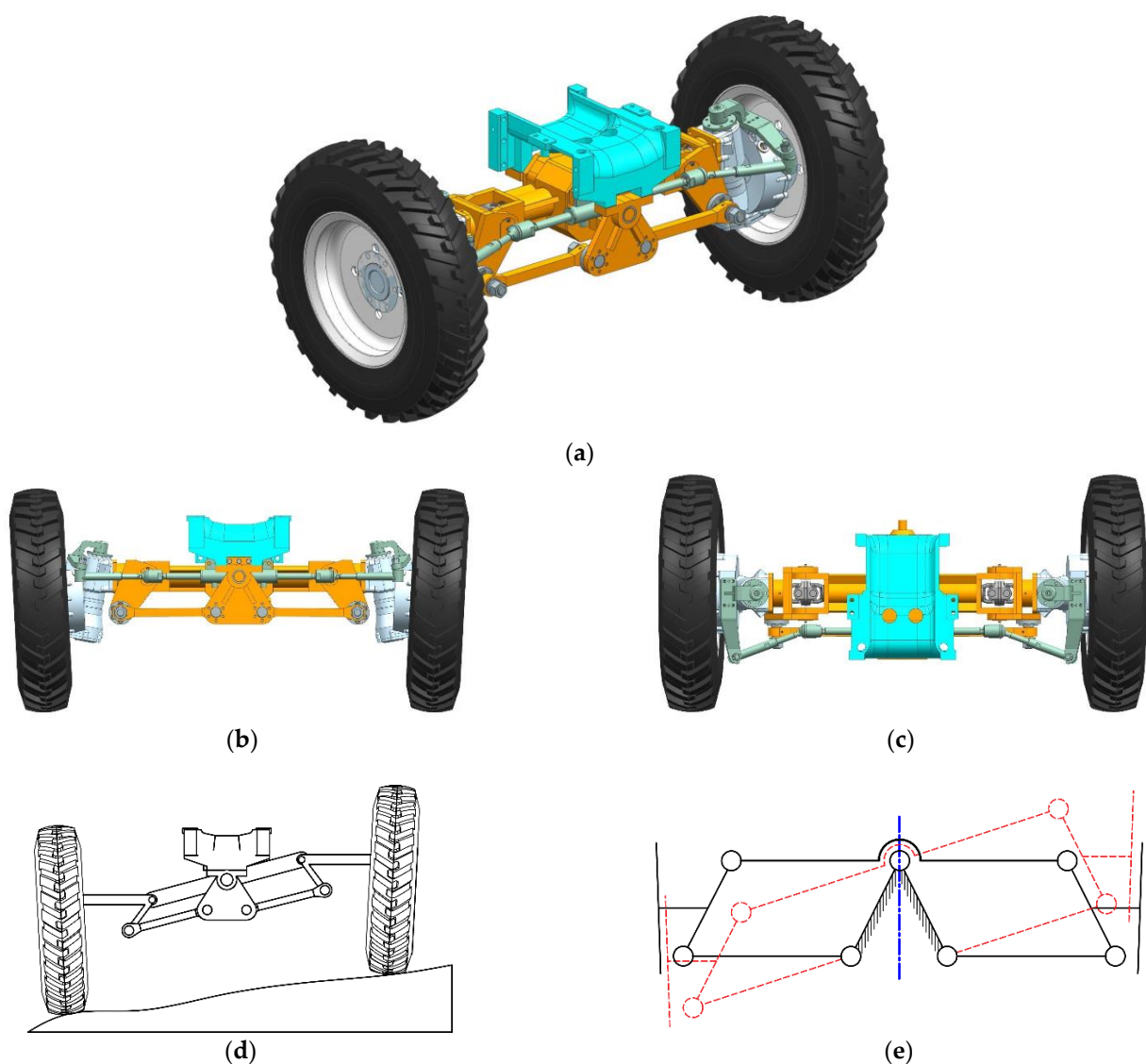

(**a**)

(**b**)   (**c**)

(**d**)   (**e**)

Figure 3. Front axle: (**a**) CAD model; (**b**) Front view model; (**c**) Top view model; (**d**) Attitude adjustment; (**e**) Principle schematic.

The tractor can passively adapt to the ground with the attitude adjustment mechanism while ensuring all four wheels keep in contact with the ground, as shown in Figure 3. With this new attitude adjustment mechanism, the angle between the front wheels and the

ground can be passively changed with the ground. Thus, the front wheels can be vertical when the tractor adjusts its attitude on side slopes. As shown in Figure 3d,e, the attitude adjustment mechanism is composed of two symmetrical four-bar linkages. The freedom of this attitude adjustment mechanism in the front wheel is:

$$F = 3 \times n - \sum_{i=1}^{n} iP_i = 3 \times 5 - 2 \times 7 = 1, \tag{1}$$

where F is the DOF, n is the number of the active components, i is the constraint number in the i level, and P_i is the number of kinematic pairs in the I level. This front axle consists of 5 active components and 7 kinematic pairs.

Thus, the DOF (degree and freedom) of this front axle is 1. It means if one rotation angle is determined, the others can be achieved. With this degree, all four wheels can keep contact with the ground while encountering small obstacles. As the adjustment mechanism is composed of two symmetrical four-bar linkages, it can be designed to adjust the lateral slopes with larger angles.

With these features of the front axle, this tractor can keep all four wheels in contact with the ground. The front axle also can cooperate with the active rear axle to actively adjust the tractor's attitude.

2.2.3. Hillside Tractor

By installing both the modified rear and front axles, this tractor is shown in Figure 4. As a kind of four-wheel-drive/front-steering one, it can keep contact with the ground on uneven terrains; it also can adjust its posture/configuration when necessary to enhance its mobility.
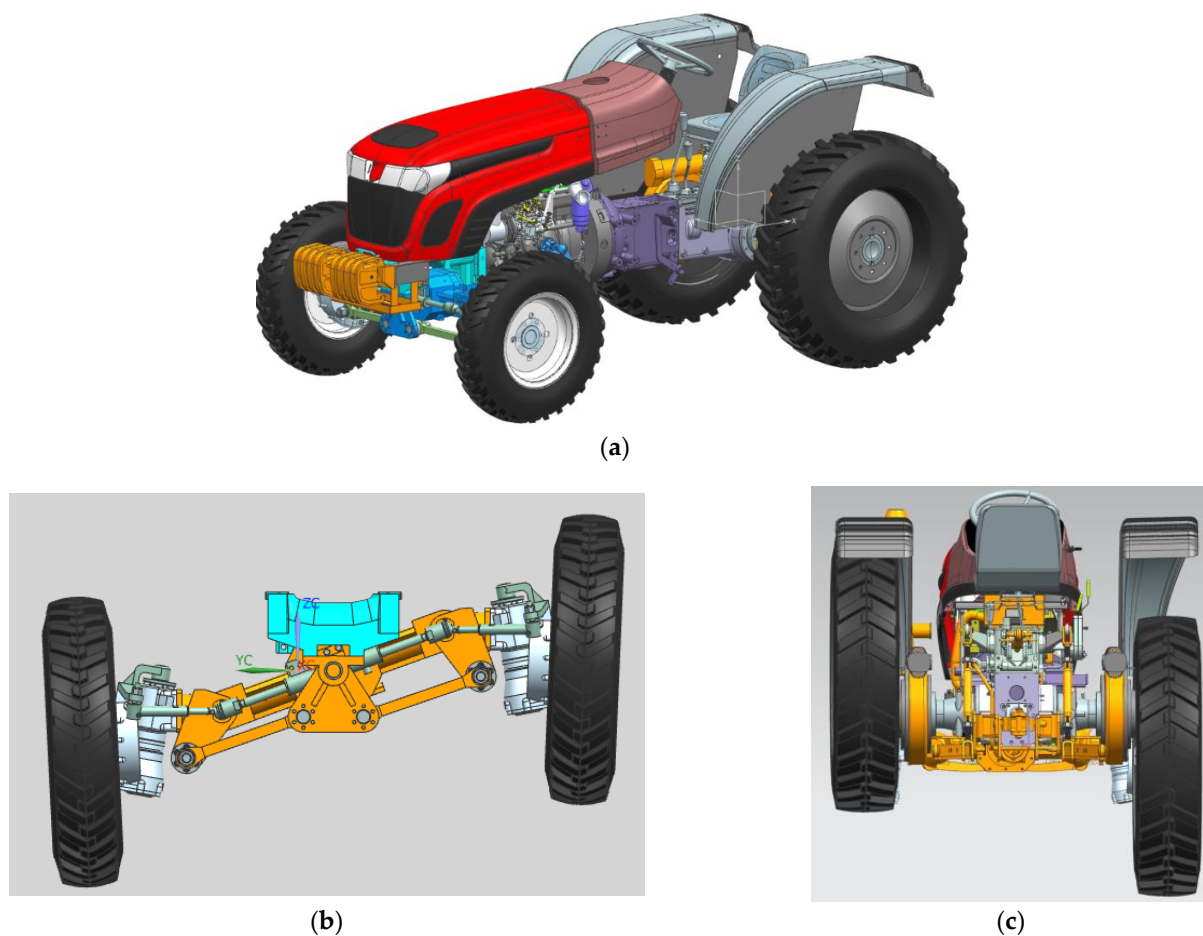

(**a**)

(**b**)

(**c**)

Figure 4. Tractor: (**a**) Whole model; (**b**) Front axle; (**c**) Rear axle.

Here are several advantages of this tractor:

- It can enhance the tractor's stability on lateral slopes by actively adjusting the adjustment mechanisms on the rear axle.
- It can move on small obstacles while ensuring all the wheels keep in contact with the ground without active control, which provides a simple control system for this tractor.
- It can level its body on side slopes, to ensure comfort for tractor drivers.

3. Adjustment Mechanism

One aim of this study is to propose a model that represents the relationship between the posture change of a tractor and its lateral stability. In addition, a tractor can actively adjust its posture using its adjustment mechanisms, which has been shown in Section 2. Consequently, two models are proposed: A complete adjustment mechanism and a tractor model. The former introduces the relationship between configuration and center of gravity (COG) of the adjustment mechanism. The latter expresses lateral stability parameters as a function of the COG on both sides. By combining these two models, the amount of stability is obtained for an arbitrary tractor model.

The aim of this section is to describe the input–output relationship of the adjustment mechanism of the designed tractor in Section 2. Based on this model, the parameters of this mechanism are also designed.

1. Mathematical model

The mathematical model of the attitude adjustment mechanism is shown in Figure 2d–f, where the rear wheel can rotate around the rotation center to change the height of COG (center of gravity).

As shown in Figure 2, the relationship between the height of COG (H) and rotation angle (α) is:

$$H(\alpha) = H_0 + L_r * sin(\alpha), \tag{2}$$

where H_0 denotes the initial height of the COG, L_r is the rotation radius, α is the rotation angle, and $\alpha \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$.

Thus, the height of COG (H) is a function with the rotation angle (α):

$$H = f(\alpha), \tag{3}$$

1. In the initial state, the height of COG is H_0.

2. When a wheel turns upward, the height of the COG becomes lower:

$$H(\alpha) = H_0 + L_r * sin(\alpha), \tag{4}$$

3. When a wheel turns downward, the height of the COG becomes higher:

$$H(\alpha) = H_0 - L_r * sin|\alpha|, \tag{5}$$

Thus, the limited positions of the height of the COG that can be achieved when a wheel turn upward/downward are:

$$\begin{cases} H(\alpha)_{\min} = H_0 - L_r \\ H(\alpha)_{\max} = H_0 + L_r \end{cases}, \tag{6}$$

2. Mechanism design

Unlike the ordinary tractor, the roll angle of the proposed tractor is changeable on lateral slopes. Hillside tractors are expected to level themselves on side slope angles in the range of 0–15°. The leveled attitude of a tractor is shown in Figure 5.
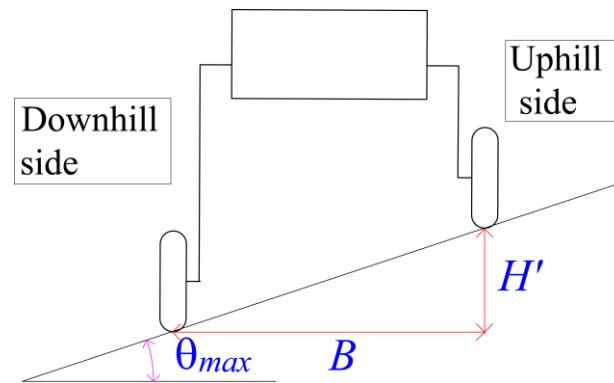
Figure 5. Leveled attitude.

Therefore, the lateral slope angle for a reconfigurable tractor to level its attitude is:

$$\theta_{\max} = arctan\left(\frac{H_{\max} - H_{\min}}{B}\right), \tag{7}$$

where B is the track width, and H_{max} and H_{min} are the maximum and minimum values of the height of COG, respectively.

Substituting Equation (6) into Equation (7) gives:

$$\theta_{\max} = arctan(2L_r/B), \tag{8}$$

where B is the track width, and L_r is the rotation radius.

The aim for designing the attitude adjustment mechanism is to level the tractor's attitude on side slope angles in the range of 0–15°, thus:

$$\theta_{\max} \geq 15°. \tag{9}$$

As shown in Figure 2d–f, design the length of rotation radius L_r:

$$L_r \geq (B * \tan 15°)/2. \tag{10}$$

Giving the tread B = 1280mm, therefore:

$$L_r \geq 171.48\text{mm}. \tag{11}$$

The distance between the half shaft and the drive shaft is 181 mm. In other words, with the rotation radius $L_r = 181$ mm, the designed parameters can satisfy the design demand. With the designed parameters, the maximum side slope angle that this tractor can level itself on is 15.79°.

4. Lateral Stability

The real safe tilt of the tractor is that this tractor is able to prevent overturning and skidding when it travels on terrains.

The tilt value mainly depends on the following factors. Exterior factors are, such as the ground conditions (slope angle and obstacle shape and height). Interior factors can be changed to adjust tractor stability, such as the moment of inertia, wheelbase, COG position, track width, ballast weight, implement position, and tire properties. Human behavioral factors of tractor drivers include speed, being in adverse environmental and weather conditions, drinking, or taking drugs [35].

Lateral overturns account for the majority of tractor accidents. In addition, posture adjustment in a tractor is a possible way to enhance locomotion performance. This designed tractor can actively adjust its roll angle to enhance its lateral stability. There-

fore, it is essential to model a tractor on a lateral slope while taking the tractor's attitude into consideration.

To analyze the effects of posture change on tractor stability on side slopes, a model is combined with a model of active mechanism and a complete tractor model. The former has been established in Section 3, describing the relationship between the input, configuration, output, and height of the COG of the adjustment mechanism. The latter is proposed in this section, introducing wheel–soil contact forces as a function of overturn parameters. By combining these two models, the instability indicator of tractor overturn is obtained for an arbitrary configuration of the tractor.

In this section, we make several assumptions to simplify the problem:

1. The tractor is equipped with four rigid wheels.
2. The steering angle of the tractor is fixed at zero.
3. The tractor travels along a flat lateral slope.
4. The traversing speed is low, and the motion of the tractor remains in a steady state.

4.1. Coordinate Systems

Here, two coordinate systems, the slope coordinate system and the tractor coordinate system, are defined. Figure 6a illustrates a tractor laterally traversing a slope of angle θ. As shown in Figure 6a, the tractor and its wheels are at a tilted angle ψ_l against the slope (ψ_l positively increases in the uphill direction). In Figure 6a, the side slope coordinate system, Σ_s, is defined as follows: $x^{(s)}$ denotes the desired traversing direction, $y^{(s)}$ denotes the uphill direction, and $z^{(s)}$ denotes the vertically upward direction against the slope surface, as a right-handed system. The tractor coordinate system, Σ_r, is achieved by a rotation of Σ_s about the $x^{(s)}$ axis with ψ_l in the uphill direction.
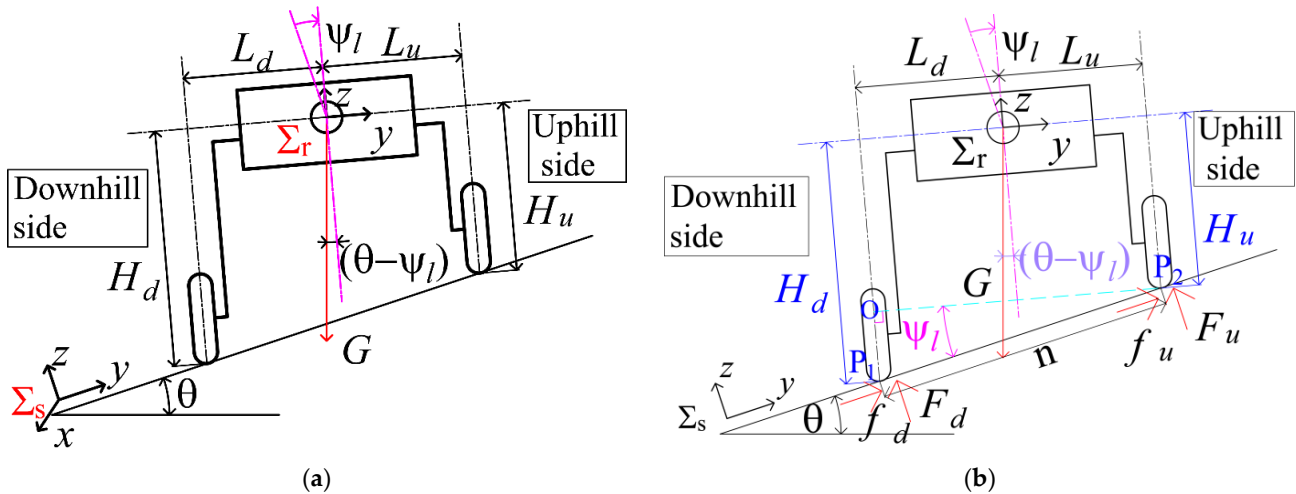

Figure 6. Tractor on a side slope: (**a**) Definition of coordinate systems; (**b**) Mechanical tractor model.

4.2. Mechanical Model of an Attitude Adjustment Tractor

In this section, we propose a mechanical model of an attitude adjustment tractor on a side slope. As shown in Figure 6a, the COG (center of gravity) of the tractor is located at distances L_d and L_u from the uphill and downhill wheels along the y_r direction, respectively, and H_d and H_u from those wheels along the z_r direction. Here, both H_d and H_u are adjusted with the input of the attitude adjustment mechanism in the rear axle, which can be obtained with Equation (2) (in Section 3), whereas both L_d and L_u are constant. Adjusting the active inputs of the rear axle on both sides together, H_d and H_u are changed. Then, the roll angle of the tractor is adjusted. Overall, the tractor can enhance its lateral stability by actively adjusting its attitude.

The aim of this section is to establish a complete tractor model, expressing the relationship between input, configure/posture and output, and wheel–soil contact force.

As shown in Figure 6b, θ_l denotes the roll angle of the tractor and ψ_l is the tilted angle of the tractor. This tractor can actively adjust its attitude at a side-slope with angle θ, thus, the roll angle of the tractor θ_l is:

$$
\begin{cases}
\text{Inital state}: \theta_l = \theta \\
\text{Attitude adjustment state}: \ \theta_l = \theta - \psi_l{'}
\end{cases}
\tag{12}
$$

As shown in Figure 6b, in the right triangle OP_1P_2, the adjustable attitude angle of the tractor with respect to the side slope (ψ_l) is:

$$
\tan(\psi_l) = \frac{H_d - H_u}{L_d + L_u}.
\tag{13}
$$

As B is the track width of the tractor:

$$
L_d + L_u = B.
\tag{14}
$$

Substituting Equation (14) into (13), the adjustable attitude angle of the tractor (ψ_l) is:

$$
\psi_l = \arctan\left(\frac{H_d - H_u}{B}\right).
\tag{15}
$$

As shown in Figure 6b, the force analysis on the side slope for an attitude adjustment tractor begins by assessing global equilibrium. The moment static equations at the uphill and downhill contact points (P_1 and P_2) are:

$$
\begin{cases}
F_u * n - G cos(\theta_l) * L_d + G sin(\theta_l) * H_d = 0 \\
-F_d * n + G cos(\theta_l) * L_d + G sin(\theta_l) * H_u = 0{'}
\end{cases}
\tag{16}
$$

where $n = \sqrt{(B)^2 + (H_d - H_u)^2}$.

After rearranging the Equation (16), equate to:

$$
\begin{cases}
\text{Uphill side}: F_u = \frac{G cos(\theta_l) * L_d - G sin(\theta_l) * H_d}{n} \\
\text{Downhill side}: F_d = \frac{G cos(\theta_l) * L_u + G sin(\theta_l) * H_u}{n}{'}
\end{cases}
\tag{17}
$$

where $n = \sqrt{(B)^2 + (H_d - H_u)^2}$, $\theta_l = \theta - \psi_l$, L_d and L_u are constant. They represent the distance between the COG and downhill/uphill wheels along the y_r direction, respectively. H_d and H_u are the distances between COG and downhill/uphill wheels along the z_r direction, respectively, which both can be actively adjusted by the input of the attitude adjustment mechanism.

4.3. Lateral Overturn Stability

Rollover will occur when the uphill side tires lose contact with the ground (the contact force falls to zero). Equation (17) becomes:

$$
\frac{G cos(\theta_l) * L_d - G sin(\theta_l) * H_d}{n} = 0,
\tag{18}
$$

where θ_{lim} is the limit instability angle of the tractor,

$$
\theta_l = \theta_{lim} - \psi_l,
\tag{19}
$$

Therefore, substituting Equations (19) and (15) into Equation (18), Equation (18) can be rearranged to obtain the limit instability angle.

- Initial state

$$\theta_{lim0} = \arctan(L_d/H_d), \tag{20}$$

In the initial state, the tractor does not adjust its attitude, and the adjustable attitude angle of the tractor (ψ_l) is 0. Thus, in the initial state, the instability angle of this tractor is equal to the ordinary one.

- Attitude adjustment state

$$\theta_{lim} = \arctan(L_d/H_d) + \arctan\left(\frac{H_d - H_u}{B}\right), \tag{21}$$

where L_d and B are constant values, and H_d and H_u vary with the input of the downhill-side and uphill-side adjustment mechanisms, respectively.

Therefore, the tractor can increase the limit instability angle by actively adjusting the values of H_d and H_u (the height of the COG on both sides) together.

Substituting Equation (20) into Equation (21) yields:

$$\theta_{lim} = \theta_{lim0} + \arctan\left(\frac{H_d - H_u}{B}\right). \tag{22}$$

Based on the above equation, by actively adjusting the attitude of an attitude adjustment tractor, the limit instability angle θ_{lim} can be larger than its initial value θ_{lim0}. As shown in Equation (22), when H_d is constant, the limit instability angle (θ_{lim}) of a reconfigurable tractor is composed of two parts: the former part is the limit instability angle at its initial state, the latter one is the adjustable attitude angle (ψ_l). In other words, a tractor can enhance its lateral overturn stability by actively adjusting its posture.

As referenced in Section 3, we denote α_u and α_d as the inputs of the active adjustment mechanisms in the uphill and downhill sides, respectively. Putting α_u and α_d into Equation (3), we obtain:

$$\begin{cases} Downhill\ side : H_d = f(\alpha_d) \\ Uphill\ side : H_u = f(\alpha_u) \end{cases}, \tag{23}$$

By substituting Equation (23) into (21), the limit instability angle θ_{lim} is:

$$\theta_{lim} = \arctan(L_d/f(\alpha_d)) + \arctan\left(\frac{f(\alpha_d) - f(\alpha_u)}{B}\right) = h(\alpha_u, \alpha_d), \tag{24}$$

where α_u and α_d as the inputs of the active adjustment mechanisms on the uphill and downhill sides, respectively.

Therefore, the limit instability angle, θ_{lim}, can be obtained by employing the inputs α_u and α_d as variables.

5. Case Study and Experiment Variation

5.1. Case Study

One purpose of this article is to investigate how the attitude adjustment technology prevents lateral rollover. A general model is presented in Section 4, representing the relationship between a tractor's posture change/configuration and stability evaluation index on transverse slopes. In this section, taking the described tractor in Section 2 as example, the effects of attitude/configuration on tractor lateral stability are studied. Calculations were performed using MATLAB software whose version number is 2021.

- Attitude adjustment mechanism

This study employs the simplest method: turning downward the downhill side wheels and turning upward the uphill side wheels by the same amount. There are three advantages of this method. First, it reduces the amount of change in the rotation angle on one side necessary for obtaining the desired attitude, and therefore it enables the tractor to actively

adapt promptly to the target terrain and continue traversing. Second, continuous roll change can be obtained around the nominal configuration. Third, during the attitude adjustment process, the wheelbases for each side are the same.

Thus, based on Equations (4) and (5), the relationship between configuration and the center of gravity (COG) of the adjustment mechanism is:

$$\begin{cases} \text{Downhill side}: H_d = f(\alpha) = H_0 + L_r * \sin|\alpha| \\ \text{Uphill side}: H_u = f(\alpha) = H_0 - L_r * \sin|\alpha| \end{cases},\tag{25}$$

where α is the rotation angle of the adjustment mechanism of the rear axle and $\alpha \in [-\pi/2, \pi/2]$, H_0 is the initial height of the COG, and L_r is the rotation radius; α can be actively adjusted, whereas both H_0 and L_r are constant values.

- Lateral stability

This section investigates the relationship between active input and lateral stability in straight-line mode. The input–output model of the adjustment mechanism is established in Section 3. A complete tractor model representing the relationship between a tractor's configuration/attitude and its lateral stability is introduced in Section 4. By combining these two models, the relationship between the active inputs of the tractor and its lateral stability can be estimated. Numerical simulation is carried out in this section with the structure parameter parameters listed in Table 1.

Table 1. Parameter values of the designed tractor.

Parameter	Value	Unit	Parameter	Value	Unit
H_0	970	mm	L_d	640	mm
L_r	181	mm	B	1280	mm

The adjustment attitude angle of a tractor, ψ_l, is obtained by substituting Equation (25) into Equation (15):

$$\psi_l = \arctan\left(\frac{H_d - H_u}{B}\right) = \arctan\left(\frac{2L_r * \sin|\alpha|}{B}\right),\tag{26}$$

The lateral instability limit angle can be deduced as putting Equation (25) into Equation (24):

1. Initial state

$$\theta_{lim} = \arctan(L_d/H_0).\tag{27}$$

2. Attitude adjustment state

$$\theta_{lim} = \arctan(L_d/H_d) + \arctan\left(\frac{H_d - H_u}{B}\right) = \arctan\left(\frac{L_d}{H_0 + L*\sin|\alpha|}\right) + \arctan\left(\frac{2L_r*\sin|\alpha|}{B}\right).\tag{28}$$

Thus, based on Equation (28), the lateral instability limit angle of a tractor, θ_{lim}, is a function of rotation angle of rear wheel, α, that is:

$$\theta_{lim} = o(\alpha),\tag{29}$$

where α is the rotation angle of the adjustment mechanism in the rear axle.

The effect of active input on the value of the attitude adjustment angle is shown in Figure 7a. The tractor can actively adjust its roll angle with attitude adjustment. The attitude adjustment angle of the tractor, ψ_l, is obtained with Equation (26). As indicated in Figure 7a, the adjustment angle ψ_l increases with increasing active rotation angle of the rear axle. The maximum value of ψ_l is 15.79°. In other words, the designed tractor can level its attitude when the slope angle is lower than 15.79°.
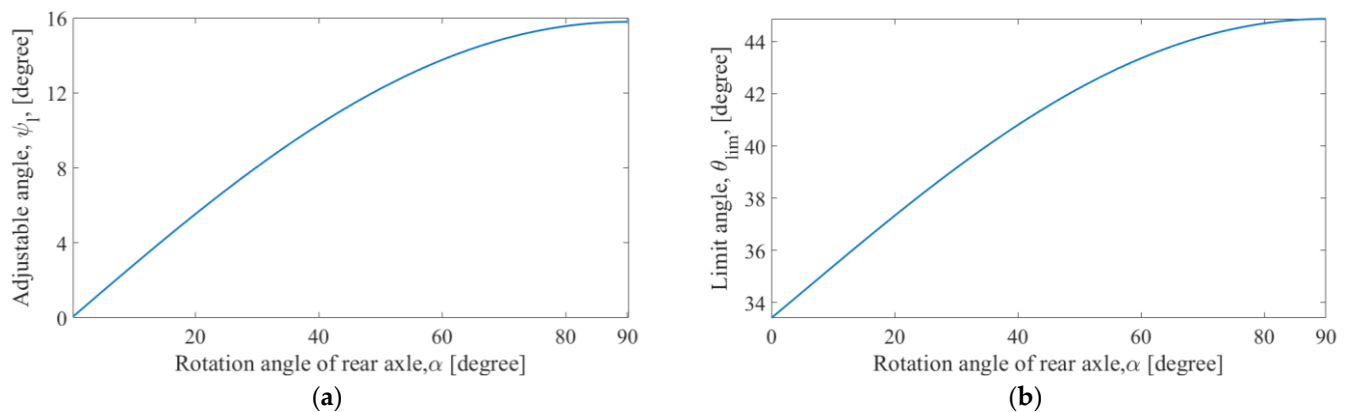
Figure 7. Lateral stability: (**a**) attitude adjustment angle; (**b**) lateral instability limit angle.

Thus, the designed tractor can level itself on a side slope whose angle is less than 15° while ensuring the comfort of tractor operators.

The effect of active input on the value of the lateral overturn indicator is shown in Figure 7b. The lateral instability limit angle (θ_{lim}) can be calculated using Equation (29). Bigger active rotation angles result in a rapid increase in overturn stability. In the initial state, when the rotation angle of the rear wheel $\alpha = 0$deg, θ_{lim} is 33.42°; when the active rotation angle obtains its maximum value, θ_{lim} is 44.87°. The lateral instability limit angle, θ_{lim}, increased 34.26%.

Overall, for the designed tractor, with the increase in active adjustment angle (α), the tractor can level its configuration to enhance the comfort of the operators; on the other hand, the lateral instability angle increases. Thus, the designed tractor can increase its overturn stability by controlling the active input of the adjustment mechanisms.

5.2. Manufacture and Test of a Prototype

5.2.1. Manufacture of a Prototype

With the process of concept, the function and structure design of the tractor are achieved. The complete prototype of the designed tractor is shown in Figure 8. It is composed of the rear axle, main body, and front axle. The tractor can achieve the attitude adjustment function with the rear axle. The steering function can be realized by the front axle. Additionally, engine and drive systems transmit power through the transfer box to both the rear and front axles, respectively. Thus, the prototype is a four-wheel-drive tractor.

Figure 8. Prototype tractor: (**a**) Front view; (**b**) Tractor.

5.2.2. Bench Tests

Some interesting tests are carried out to check the practical performances of this tractor. The tractor can achieve basic functions, such as move forward, back, and turn. It not only can adjust its attitude, but also can level itself on side slope angles in the range of 0–15°.

The previous model is solved using MATLAB software. In this section, we use bench tests to verify the lateral stability of the designed tractor. As shown in Figure 9, the test equipment is the roll test bench. This test bench is equipped with a slope-measuring instrument connected to the computer. The computer can read the slope angle data in real time.

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

Figure 9. Bench tests: (**a**) Initial state; (**b**) Attitude adjustment.

While ensuring the safety of this prototype, this tractor is braked on this test bench. In the initial state, the prototype is leveled. Then, with the increase in the slope angle, the contact force between the wheel and slope changes. The overturning of the prototype with the test bench can be observed. When the contact force between the wheel and slope is less than or equal to zero, this tractor overturns.

As shown in Figure 9, the working conditions can be divided into initial state and attitude adjustment, respectively. The designed tractor can actively adjust its posture on side slopes with the mechanisms installed on the rear axle. (1) First, a tractor in its initial state is braked on the bench, with the increase in slope angle, the contact force between the wheel and slope changes. When the slope angle is 30.91°, the uphill rear wheel leaves the ground, then the tractor overturns. (2) Then, the test tractor equipped with an adjusted attitude function is braked on the bench, as increasing lateral slope angle, the contact force between the wheel and slope changes. When the slope angle is 40.74°, the uphill rear wheel leaves the ground, then the tractor overturns. Results show that by actively adjusting the roll angle of the tractor, the limit instability angle increases from 30.91° to 40.74°.

The mathematical model is presented in Section 4, representing the relationship between a tractor's posture change/configuration and stability evaluation index on transverse slopes. First, the force model on side slopes is built to obtain the limit instability angle (θ_{lim}). Then, taking the proposed tractor, for example, the effects of attitude/configuration on tractor lateral stability are studied in Section 5.1. Theoretical analysis shows that the lateral stability can be enhanced by adjusting the tractor's attitude. The limit instability angle (θ_{lim}) can be increased by increasing the active input (rotation angle of the rear axle, α). In the initial state, θ_{lim} is 33.42°; when the rotation angle of the rear axle (α) is 90°, θ_{lim} turns 44.87° (increased 34.26%).

As shown in Figure 10, the lateral stability solutions with the mathematical model in Section 4 are compared with the results of bench tests in this section. The working conditions are divided into initial state and attitude adjustment. In the initial state, the difference between theory (33.42°) and test results (30.91°) is 8.12%. After attitude adjustment, the difference between theory (44.87°) and test results (40.74°) is 10.14%.
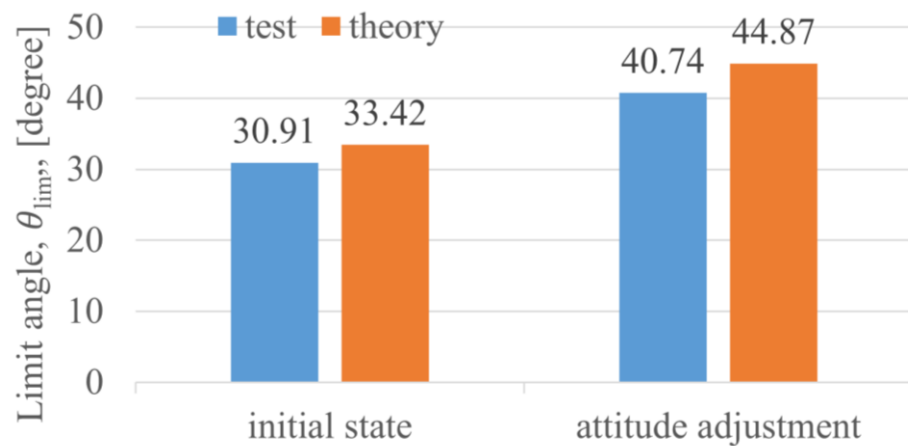
Figure 10. Lateral stability in theory and test modes.

There are two possible reasons for the difference (10%) between the theory model in Section 4 and bench tests in Section 5.2.2: (1) In the theory model, the wheel is assumed as a rigid model, and the wheel's deformation is not considered. On the other hand, the wheels in the tests are low-pressure tires, and they will become deformed; (2) The uphill/downhill sides tires are considered as a whole to establish the mechanical model. Meanwhile, the rear wheel on the uphill side loses contact with the ground in the test. Therefore, the lateral stability method developed in Section 4 is accurate enough to bring a potential model to the actual solution.

Results show that a tractor is able to increase its lateral stability by properly adjusting its configuration/posture, to avoid fatal accidents related to lateral overturns. In addition, the designed tractor can actively adjust its configuration/roll angle, to enhance the lateral overturn stability. More specifically, the configuration is changed by adjusting the rotation angle of the slewing bearing on both downhill and uphill sides.

6. Conclusions and Future Works

A tractor with an attitude adjustment function is designed and developed to traverse on side slopes. The lateral stability is also investigated while taking configuration/posture into consideration.

Inspired by the traditional tractor, a method to adjust attitude is described. Corresponding mechanisms are also designed to adjust the tractor's posture, adapt terrains, and transfer power. This tractor exhibits two locomotion modes. In the first mode, it can work under uneven terrains while keeping the four wheels in contact with the ground without needing sensors. In the second mode, the tractor can adjust the roll angle in the case that slopes or larger obstacles are encountered. Meanwhile, a leveled attitude is obtained to ensure drivers' comfort.

Thus, this four-wheel-drive tractor is able to maintain stability in various situations (especially side slopes and uneven terrains) with a simple control system. The tractor presented in this paper thus has provided new insights into the design of tractors with multiple motion modes, which has potential application in the fields of hilly and mountainous terrains.

Tractor stability against a lateral overturn is known to be determined by multiple factors [1,36]. Exterior factors such as the ground conditions (slope angle and obstacle shape and height) cannot be controlled [2,37]. Thus, interior factors can be changed to adjust tractor stability. Fortunately, factors such as the moment of inertia, wheelbase, COG position, track width, ballast weight, implement position, and tire properties affecting tractor stability have been clearly explored in previous studies [1,8,13,38–40]. However, attitude adjustment technology, which can actively adjust a tractor's configuration and posture, has not been considered in previous studies. With specific attitude adjustment

mechanisms, a tractor can adjust its configuration and posture to enhance its stability and trafficability.

Therefore, this study also analyzes the effects of posture change on tractor stability on side slopes. A mechanical model relating the configuration of the tractor to its lateral stability is presented. A static study for evaluating the lateral stability of a tractor possibly suitable for working on hilly and mountainous terrains has been made. This developed model allows to treat an attitude adjustment tractor and forests the instability conditions with active inputs. Meanwhile, several conditions are not considered in the proposed model, e.g., steering radius, speed, tire deflection, and soft road.

Taking the designed tractor with attitude adjustment mechanisms into consideration, the above model and the stability conditions have been implemented in a MATLAB simulator and they have been validated by means of an experimental emulator. With the designed attitude adjustment mechanism, the designed tractor can actively adjust its roll angle. This tractor can also level itself when the angle of the side slope is less than $15.79°$. The results of numerical simulation show that lateral overturn stability increases while adjusting the configuration. lateral instability limit angle (θ_{lim}) increases from $33.42°$ to $44.87°$. A prototype is developed and the reliability of these models is examined through bench tests. The results of numerical simulation show similar tendencies to those of the experiments.

Overall, adjusting the tractor's attitude can reduce lateral overturn. The approach developed here provides an effective way to enhance a tractor's lateral stability. In addition, the leveled posture can be considered as an appropriate configuration to ensure the drivers' comfort and stability.

Future work will be devoted to the extension of the model in the (quasi-)static and dynamic study for evaluating the stability of a general tractor with posture change. The future model should take into account steering radius, speed, and wheel–terrain interactions in non-standard operation conditions.

References

1. Li, Z.; Inoue, M.; Okayasu, E.; Hirai, T.; Zhu, Y.; Xiang, Z. Parameter sensitivity for tractor lateral stability against Phase I overturn on random road surfaces. *Biosyst. Eng.* **2016**, *150*, 10–23. [CrossRef]
2. Jang, M.-K.; Hwang, S.-J.; Nam, J.-S. Simulation Study for Overturning and Rollover Characteristics of a Tractor with an Implement on a Hard Surface. *Agronomy* **2022**, *12*, 3093. [CrossRef]
3. He, Z.; Song, Z.; Wang, L.; Zhou, X.; Gao, J.; Wang, K.; Li, Z. Fasting the stabilization response for prevention of tractor rollover using active steering: Controller parameter optimization and real-vehicle dynamic tests. *Comput. Electron. Agric.* **2023**, *204*, 107525. [CrossRef]

4. Franceschetti, B.; Rondelli, V.; Capacci, E. Lateral Stability Performance of Articulated Narrow-Track Tractors. *Agronomy* **2021**, *11*, 2512. [CrossRef]

5. Guzzomi, A.L. A revised kineto-static model for Phase I tractor rollover. *Biosyst. Eng.* **2012**, *113*, 65–75. [CrossRef]

6. Qin, J.; Zhu, Z.; Ji, H.; Zhu, Z.; Li, Z.; Du, Y.; Mao, E. Simulation of active steering control for the prevention of tractor dynamic rollover on random road surfaces. *Biosyst. Eng.* **2019**, *185*, 135–149. [CrossRef]

7. Kang, S.; Kim, Y.; Park, H.; Kim, Y.; Woo, S.; Uyeh, D.D.; Ha, Y. Rollover Safety and Workable Boundary Suggestion of an Agricultural Platform with Different Attachments. *Agriculture* **2022**, *12*, 1148. [CrossRef]

8. Baker, V.; Guzzomi, A.L. A model and comparison of 4-wheel-drive fixed-chassis tractor rollover during Phase I. *Biosyst. Eng.* **2013**, *116*, 179–189. [CrossRef]

9. Li, Z.; Mitsuoka, M.; Inoue, E.; Okayasu, T.; Hirai, Y. Development of stability indicators for dynamic Phase I overturn of conventional farm tractors with front axle pivot. *Biosyst. Eng.* **2015**, *134*, 55–67. [CrossRef]

10. Li, Z.; Mitsuoka, M.; Inoue, E.; Okayasu, T.; Zhu, Z. Modification of a Tractor Dynamic Model Considering the Rotatable Front End. *J. Fac. Agric. Kyushu Univ.* **2015**, *60*, 219–224. [CrossRef]

11. Watanabe, M.; Sakai, K. Numerical analysis of steering instability in an agricultural tractor induced by bouncing and sliding. *Biosyst. Eng.* **2020**, *192*, 108–116. [CrossRef]

12. Li, Z.; Mitsuoka, M.; Inoue, E.; Okayasu, T.; Hirai, Y. Dynamic analysis of agricultural wheel tractor driving on uneven surface under the influences of speed and slope angle. *J. Fac. Agric. Kyushu Univ.* **2014**, *59*, 339–343. [CrossRef]

13. Ahmadi, I. Development of a tractor dynamic stability index calculator utilizing some tractor specifications. *Sci. Technol. Res. Counc. Turk.* **2013**, *37*, 203–211. [CrossRef]

14. Vidoni, R.; Bietresato, M.; Gasparetto, A.; Mazzetto, F. Evaluation and stability comparison of different vehicle configurations for robotic agricultural operations on side-slopes. *Biosyst. Eng.* **2015**, *129*, 197–211. [CrossRef]

15. Zhu, Y.; Kan, J. Prediction of the lateral stability of a forestry chassis with an articulated body and fitted with luffing wheel-legs. *Biosyst. Eng.* **2022**, *224*, 143–160. [CrossRef]

16. Zirong, L.; Jianzhong, S.; Guowu, W.; Lei, R. A reconfigurable hybrid wheel-track mobile robot based on Watt II six-bar linkage. *Mech. Mach. Theory* **2018**, *128*, 16–32.

17. Inotsume, H.; Sutoh, M.; Nagaoka, K.; Nagatani, K.; Yoshida, K. Modeling, Analysis, and Control of an Actively Reconfigurable Planetary Rover for Traversing Slopes Covered with Loose Soil. *J. Field Robot.* **2013**, *30*, 875–896. [CrossRef]

18. Cordes, F.; Dettmann, A.; Kirchner, F. Locomotion modes for a hybrid wheeled-leg planetary rover. In Proceedings of the IEEE International Conference on Robotics & Biomimetics, Phuket, Thailand, 7–11 December 2011.

19. Iagnemma, K.; Rzepniewski, A.; Dubowsky, S.; Pirjanian, P.; Huntsberger, T.; Schenker, P. Mobile robot kinematic reconfigurability for rough-terrain. In Proceedings of the Conference on Sensor Fusion and Decentralized Control in Robotic System, Boston, MA, USA, 6–8 November 2000.

20. Wettergreen, D.; Moreland, S.; Skonieczny, K.; Jonak, D.; Kohanbash, D.; Teza, J. Design and field experimentation of a prototype Lunar prospector. *Int. J. Robot. Res.* **2010**, *29*, 1550–1564. [CrossRef]

21. Wilcox, B.H.; Litwin, T.; Biesiadecki, J.J.; Matthews, J.; Heverly, M.; Morrison, J.; Cooper, B.K. Athlete: A cargo handling and manipulation robot for the moon. *J. Field Robot.* **2007**, *24*, 421–434. [CrossRef]

22. Aoki, T.; Murayama, Y.; Hirose, S. Development of a Transformable Three-wheeled Lunar Rover: Tri-Star IV. *J. Field Robot.* **2013**, *31*, 206–223. [CrossRef]

23. Halme, A.; Leppänen, I.; Salmi, S.; Ylönen, S. Hybrid locomotion of a wheel-legged machine. In Proceedings of the 3rd International Conference on Climbing and Walking Robots (CLAWAR'00), Madrid, Spain, 15 October 2000.

24. Reid, W.; Perez-Grau, F.J.; Goktogan, A.H.; Sukkarieh, S. Actively articulated suspension for a wheel-on-leg rover operating on a Martian analog surface. In Proceedings of the 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden, 16–21 May 2016.

25. Grand, C.; Benamar, F.; Plumet, F.; Bidaud, P. Stability and Traction Optimization of a Reconfigurable Wheel-Legged Robot. *Int. J. Robot. Res.* **2016**, *23*, 1041–1058. [CrossRef]

26. Jiang, H.; Xu, G.; Zeng, W.; Gao, F. Design and kinematic modeling of a passively-actively transformable mobile robot. *Mech. Mach. Theory* **2019**, *142*, 103591. [CrossRef]

27. Mashadi, B.; Hanif, N. Automatic Control of a Modified Tractor to Work on Steep Side Slopes. *J. Terramech.* **2009**, *46*, 299–311. [CrossRef]

28. Aziz RM, S.; Samieifar, A.; Mehrabani, M.H.; Khaqanifar, M. Design and Manufacture of an Appropriate Suspension Mechanism for the Wheels of the Tractor for Moving on Transveral slopes. *Int. J. Agric. Crop Sci.* **2014**, *7*, 1406–1416.

29. Gao, Q.; Gao, F.; Tian, L.; Li, L.; Jiang, D. Design and development of a variable ground clearance, variable wheel track self-leveling hillside vehicle power chassis (V2-HVPC). *J. Terramech.* **2014**, *56*, 77–90. [CrossRef]

30. Wang, Y.J.; Yang, F.Z.; Pan, G.T.; Liu, H.Y.; Zhang, J.Q. Design and Testing of a Small Remote-Control Hillside Tractor. *Trans. ASABE Am. Soc. Agric. Biol. Eng.* **2014**, *57*, 363–370.

31. Peng, H.; Ma, W.; Zhao, E.; Lu, X.; Feng, X. Design and physical model experiment of body leveling system for roller tractor in hilly and mountainous region. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 36–44.

32. He, P.; Wen-xing, M.; Zhong-shan, W. Control system of self-leveling in hilly tractor body through simulation and experiment. *J. Jilin Univ. Eng. Technol. Ed.* **2019**, *49*, 157–165.

33. Sun, J.; Meng, C.; Zhang, Y.; Chu, G.; Zhang, Y.; Yang, F.; Liu, Z. Design and physical model experiment of an attitude adjustment device for a crawler tractor in hilly and mountainous regions. *Inf. Process. Agric.* **2020**, *7*, 466–478. [CrossRef]

34. Jiang, H.; Xu, G.; Zeng, W.; Gao, F.; Chong, K. Lateral Stability of a Mobile Robot Utilizing an Active Adjustable Suspension. *Appl. Sci.* **2019**, *9*, 4410. [CrossRef]

35. Moreschi, C.; Da Broi, U.; Cividino, S.R.S.; Gubiani, R.; Pergher, G.; Vello, M.; Rinaldi, F. The analysis of the cause-effect relation between tractor overturns and traumatic lesions suffered by drivers and passengers: A crucial step in the reconstruction of accident dynamics and the improvement of prevention. *Agriculture* **2017**, *7*, 97. [CrossRef]

36. Song, Z.; Wang, L.; Liu, Y.; Wang, K.; He, Z.; Zhu, Z.; Qin, J.; Li, Z. Actively steering a wheeled tractor against potential rollover using a sliding-mode control algorithm: Scaled physical test. *Biosyst. Eng.* **2022**, *213*, 13–29. [CrossRef]

37. Jang, M.K.; Hwang, S.J.; Kim, J.H.; Nam, J.S. Overturning and rollover characteristics of a tractor through dynamic simulations: Effect of slope angle and obstacles on a hard surface. *Biosyst. Eng.* **2022**, *219*, 11–24. [CrossRef]

38. Gravalos, I.; Gialamas, T.; Loutridis, S.; Moshou, D.; Kateris, D.; Xyradakis, P.; Tsiropoulos, Z. An experimental study on the impact of the rear track width on the stability of agricultural tractors using a test bench. *J. Terramech.* **2011**, *48*, 319–323. [CrossRef]

39. Takeda, J.; Shimada, M.; Kikuchi, Y.; Nakano, M.; Okada, S.; Hiroma, T.; Torisu, R. Dynamic behaviors of farm tractor passing over an obstacle (Part 1) improvement of tractor dynamic model and measurement of tire stiffness. *J. Jpn. Soc. Agric. Mach.* **2010**, *72*, 457–463.

40. Franceschetti, V.C.A. Comparing the influence of roll-over protective structure type on tractor lateral stability. *Saf. Sci.* **2019**, *115*, 42–50. [CrossRef]