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AddTraX: Traction Enhancement of Tractors Using Additive Motor-Integrated Driving Wheel Units

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Abstract— **This study proposes a novel concept of an electric tractor that can flexibly respond to tasks with different traction force requirements. The key idea is to attach motor-integrated additive driving wheel units (AddTraX) to the rear wheel of the tractor according to the required traction force. The required functions for the driving wheel units are to allow manual attachment of the driving wheel units by the operator, and to control the height of the driving wheel units while running so that all the wheels have contact with ground. Driving experiments have been conducted using a single-side 1/4 scale model of the proposed driving wheel units and simply implemented models of several road conditions. On a paved road, the attachment of the additional driving wheel units enhance the traction force by 1.9 times, and wheel height control is unnecessary. On a soft unpaved road, traction force is increased by controlling the height of the driving wheel units when the vehicle weight is low. Furthermore, the experiment also confirms that the additional driving wheel units can help the vehicle overcoming steps on uneven road.**

I. INTRODUCTION

As a countermeasure against global warming, there is a growing demand for the electrification of agricultural tractors. In Japan's agriculture, forestry, and fisheries sector, 30.7% of greenhouse gas emissions are carbon dioxide, most of which originates from fuel combustion for operating machinery such as tractors. Therefore, reducing fuel consumption is essential for achieving carbon neutrality. Several agricultural machinery manufacturers are developing electric tractors to reduce the use of fossil fuels.

Tractors are produced in a wide range of sizes to meet the traction force requirements of different tasks, since the required traction force can vary by more than twice depending on the type of operation. Consequently, some farmers use medium- to large-sized tractors for tasks such as tillage, which require high traction force, and small-sized tractors for lighter tasks such as fertilizer application. Increasing the utilization rate of each machine contributes to resource conservation, and there is a demand for electric tractors that can handle both high- and low-traction tasks.

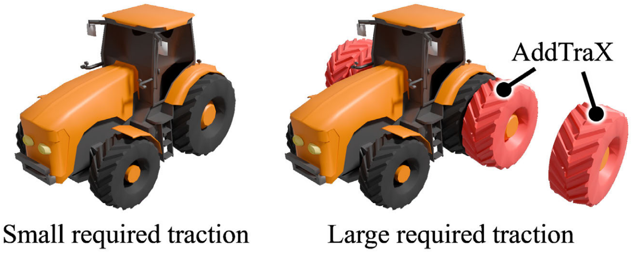

Fig. 1. Proposed electric tractor concept with additive driving wheel units

To address these issue, this study proposes a novel approach, as illustrated in Fig. 1: attaching driving wheel units (AddTraX) equipped with tires and motors according to the traction force required for each task. This enables a single tractor to flexibly accommodate different traction requirements. AddTraX stands for ”adding” ”traction”.

The contributions of this study are summarized as follows. (1) We propose additive driving wheel units called AddTraX to enable a single tractor to perform various tasks requiring both high and low levels of traction force. (2) We have designed a feasible driving wheel unit satisfying the above required functions, and verify its practicality through traction experiments. (3) We have developed a concise sensing method for control system of proposing wheel units, and the experiment results demonstrate its effectiveness.

The rest of this paper is organized as follow. Section II reviews previous studies on traction enhancement and driving units modularization, and discusses their limitations and problems to be addressed. Section III describes the required functions of the proposed driving wheel units and the approach to achieve them. Section IV presents the implementation of a $1/4$ scale model of the driving wheel units, as well as the development of their control method, based on the approach. Section V reports traction experiments conducted on simply implemented road models using the scale model developed in Section IV. Finally, Section VI concludes the paper.

II. RELATED WORKS

Several previous studies tried to enhance vehicle traction by modifying the material of the wheels or the structural design of the vehicle body. For example, some studies have investigated the use of high-rigidity lugs for tractor tires [1], while others have examined changes in the height of the tractor's hitch point [2]. Although these approaches directly contribute to improving traction performance, the resulting increase of traction force are limited to several percent to a few tens of percent. This is insufficient to realize more than twofold variations in required traction force in actual

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agricultural operations.

Examples of functionalizing driving wheels for other than tractors include studies that estimate traction force using force sensor arrays mounted on the tire circumference [3], estimate tire load with accelerometers embedded inside the tire [4], and monitor tire pressure with pressure sensors installed within the tire [5][6]. These approaches aim to improve vehicle controllability through data acquisition or to prevent accidents by detecting abnormalities. Although various ideas for adding functions to driving wheels have been proposed, none of them specifically aim to enhance traction force. This can be attributed to the conventional view that traction enhancement is achieved by increasing the output of power sources such as engines or motors. In general, however, increasing the output of the power source leads to an increase in vehicle weight. In the agricultural domain, excessive soil compaction can negatively affect crop growth. Therefore, it is necessary to keep ground contact pressure as low as possible. Consequently, there is a need for methods to enhance vehicle traction force avoiding the effect of mass increase from higher power output. This study aims to increase traction force through a new approach of attaching additive driving wheel units, and to realize a tractor to perform multiple tasks with different traction requirements.

In the field of cooperative transport using multiple driving units, previous studies have demonstrated approaches such as connecting multiple drones to increase payload capacity [7][8] and employing multiple mobile units to transport automobiles [9]. However, cooperative traction on unpaved roads with soft or uneven surfaces has not yet been realized. Traditionally, traction vehicles have had little necessity to reduce their own weight, and thus the benefits of modularizing the driving units were considered limited. In contrast, modularization of driving units offers a unique advantage. Since both the power source (e.g., motor) and the ground-contacting element (e.g., tire) are added together, the ratio of vehicle weight to contact area remains approximately constant before and after the addition. This allows traction force to be enhanced without explicit increase of ground contact pressure. Therefore, the modularization of driving units is expected to have enough benefits to be considered in the agricultural domain, where maintaining low soil compaction is essential. In addition, the modularized driving wheel units can be attached or detached manually by the operator, allowing flexible response to tasks with different traction requirements.

In terms of drive unit control, various traction control strategies have been applied to in-wheel motors. In-wheel motor stands for the structure that places the motor inside the wheel, enabling compact drive units and offering high controllability [10]. Based on this high controllability, several types of traction control have been studied, such as slip-ratio control for stable driving on slippery roads [11] and traction distribution among wheels according to the ratio of normal force of each wheel for unpaved road driving [12]. However, these previous studies assume that each driving wheel can independently satisfy the required traction force, while the proposing tractor aims to handle high-traction tasks using multiple driving wheel units each of which has insufficient traction. Therefore, they cannot be applied to the cooperative traction approach of this study.

In summary, previous studies are not suitable for the objectives of this research because of following reasons. (1) The increase in traction force is limited. (2) Functionalizing wheels do not aim at traction enhancement. (3) Cooperative traction on unpaved road is not addressed. (4) Traction control assumes that each driving unit independently provides sufficient traction force.

III. ADDITIVE DRIVING WHEEL UNITS FOR TRACTION ENHANCEMENT

This section clarifies the required functions of the proposed additive driving wheel units from the perspectives of unit operation and functionality, and examines approaches to realize them.

A. *Required Functions for Additive Driving Wheel Units*

The required functions for the driving wheel units to enhance traction force are defined as follows. Manual attachment of driving wheel units (RF1): Operators must be able to manually attach the driving wheel units according to the traction force required for a given agricultural task. Effective traction from all driving wheels (RF2): Both the existing wheels and the additionally attached driving wheel units must be able to generate traction force, accommodating changes in ground contact conditions.

B. *Approach to Realize Manual Attachment of Driving Wheel Units*

This section considers the structural configuration of the driving wheel unit to enable manual attachment (RF1).

Three candidate layouts of the driving motor relative to the wheel are illustrated in Fig. 2: (a-1) axial location, (a-2) radial location, and (a-3) in-wheel location. Among these, in the axial (a-1) and radial (a-2) location, the motor would be positioned outside tractor wheels with diameters ranging from 800 mm to 1500 mm. This makes the driving wheel unit too large to be handled manually by the operator. In contrast, the in-wheel location (a-3) has fewer external structural components and is therefore more suitable for driving wheel unit that are required to be attached manually. Accordingly, this study adopts the in-wheel location (a-3) for the driving wheel unit structure.

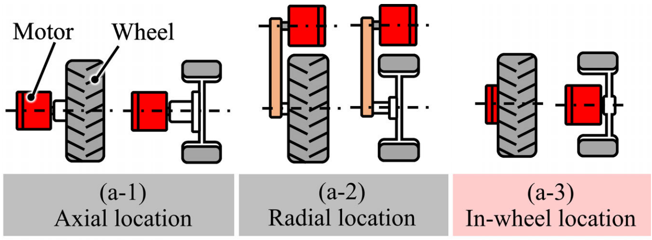


Fig. 2. Comparison of wheel-motor locations

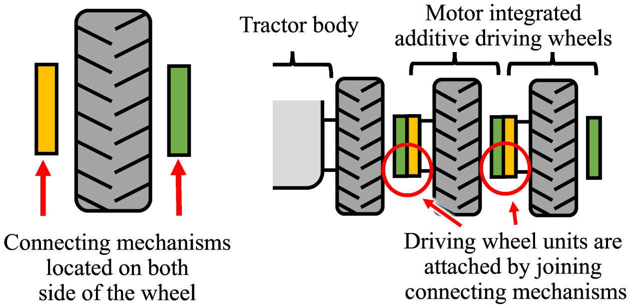
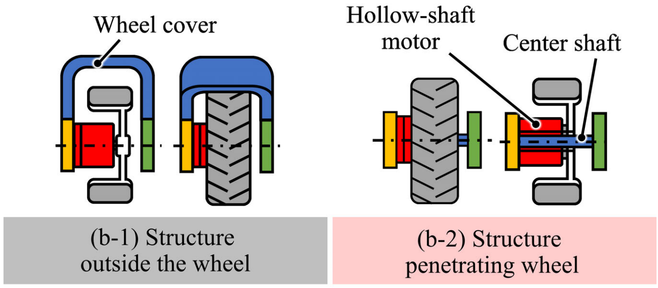


Fig. 3. Location of driving wheel unit connecting mechanisms



(b-1) Structure outside the wheel

(b-2) Structure penetrating wheel

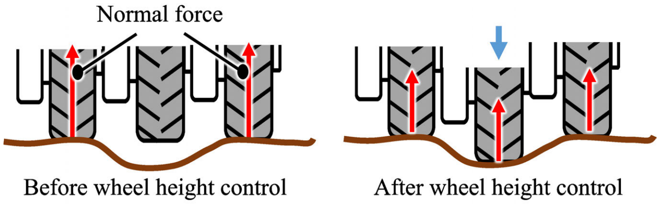
Fig. 4. Comparison of structure to fix the connecting mechanism

As shown in Fig. 3, the driving wheel unit is connected through connecting mechanisms at both ends. Two candidate structures for fixing the connection mechanism are illustrated in Fig. 4: (b-1) structure outside the wheel, and (b-2) structure penetrating the wheel. Since the structure penetrating the wheel (b-2) has fewer external components, it allows easier handling by the operator and is therefore considered more suitable as a fixing structure for the connection mechanism. Accordingly, this study adopts the structure penetrating the wheel (b-2).

C. Approach to Realize Effective Traction from All Driving Wheels

This section discusses the necessary mechanisms and their control methods to realize effective traction from all driving wheels (RF2).

For all driving wheels to generate traction force after additional units are attached, each wheel must be in contact with the ground so that a sufficient normal force is applied. On flat paved roads, the additional units are expected to contact the ground without any special measures. However, on unpaved roads such as agricultural fields, due to its soft and uneven surface, some driving wheels may lose ground contact. To address this issue, we propose a wheel elevating mechanism. This mechanism enables height changes of wheels to maintain ground contact. As illustrated in Fig. 5, the normal forces acting on each driving wheel are measured during traction operation, and the wheel heights are controlled to equalize these forces. In this way, all wheels are expected to remain in contact with the ground, allowing every driving wheel unit to generate traction force even on unpaved roads.



Before wheel height control

After wheel height control

Fig. 5. Concept of height control for driving wheel units

D. Research Approach

In this study, we develop a scale model of motor-integrated additive driving wheel units that satisfy the required functions (RF1) and (RF2) in order to verify their feasibility through traction experiments.

The proposed driving wheel unit is designed to serve as the minimum modular element of an agricultural tractor. The rear wheels of typical small tractors in Japan have a diameter of approximately $1000\,\mathrm{mm}$, and the model adopts a $1/4$ scale in wheel diameter ($250\,\mathrm{mm}$). Since the purpose of this study is to verify the feasibility of proposing cooperative traction using the driving wheel units, the scale model experiments are considered sufficient. Furthermore, to simplify the experimental setup, straight-line traction tests are conducted using only single-side wheel units. This configuration is justified by the fact that heavy-traction tasks such as tillage are generally performed during straight-line operation, where wheel motion can be assumed symmetric to the vehicle. In addition, considering that electrification may increase vehicle weight due to battery installation, traction experiments are also conducted under varying vehicle weights to evaluate the effect of weight increase on traction performance.

IV. DESIGN AND IMPLEMENTATION OF THE DRIVING WHEEL UNITS

This section describes the design and implementation of the $1/4$ scale model of the proposed driving wheel units. In addition, a height controller for the driving wheels to enable traction experiments is designed.

A. Overall Structure of the Driving Wheel Units

Fig. 6 shows the developed $1/4$ scale model. The motor-integrated additive driving wheel unit consists of three main components: a driving part for rotating the wheel with motor inside, a connecting mechanism for coupling with other units, and a elevating mechanism for controlling the wheel height. The connecting and elevating mechanisms are installed at each end of the driving part. Each driving wheel unit weights $6.8\,\mathrm{kg}$.

B. Design of the Driving Part

The driving part has a motor inside the wheel and is designed to allow the assembly of both the connecting mechanism and the elevating mechanism. As shown on the left side of Fig. 7, the wheel is directly mounted to the motor so that as much as possible volume of the motor is located inside the wheel. A center shaft passing through both the hollow-shaft motor and the wheel supports the connecting mechanism. As illustrated on the right side of Fig. 7, two bushings fixed to the motor housing provide vertical sliding motion along the linear shaft located inside the elevating mechanism.

C. *Design of the Connecting Mechanism*

The connecting mechanism is required to enable manual attachment, provide high rigidity, and allow easy alignment during connection. As shown on the left side of Fig. 8, a button lock clamp is employed to achieve manual connection. The right side of Fig. 8 illustrates a 3D CAD model of the connection mechanism. A center shaft that fixes the connecting mechanism is inserted into the housing of the adjoining driving wheel unit, thereby enhancing the rigidity of the joint. In addition, a rough guide pin is installed to realize easier alignment during the connection process.

D. *Design of the Elevating Mechanism*

The elevating mechanism is required to enable vertical movement of the driving part and allow estimation of the normal force applied to the wheel. Fig. 9 shows snapshots of the implemented mechanism. The movable part slides vertically along two linear shafts and is driven up and down by a ball screw actuated by a servo motor. Furthermore, as shown on the right side of Fig. 9, a spring is placed between the movable part and the motor housing that receives the normal force. Fig. 10 illustrates the normal force estimation mechanism, where k represents the spring constant, x is the spring displacement, and W is the weight of the driving part. The normal force N is calculated as follows:

$$N = kx + W$$

E. *Height Control of the Driving Wheel Units*

The wheel height controller is required to adjust the wheel height while running so that all driving wheels remain in contact with the ground. Using the normal force estimation method described in section IV-D, the controller adjusts wheel height to equalize the estimated normal forces among all driving wheels. A block diagram of the controller is shown in Fig. 11, where N represents the estimated normal force and N_{ref} represents the target normal force. First, the total sum of the estimated normal forces of all driving wheels N_i gained from the normal force estimation method is divided by the number of wheels n, and this value is set as the target normal force for each wheel.

$$N_{\text{ref}} = \frac{1}{n} \sum_{i=1}^{n} N_i$$

Subsequently, each wheel is moved upward or downward so that its estimated normal force N matches the target value N_{ref}. When the estimated normal force exceeds the target, the wheel is lifted. Conversely, when the estimated normal force is below the target, the wheel is lowered. This control loop is repeated continuously while the vehicle is in operation.

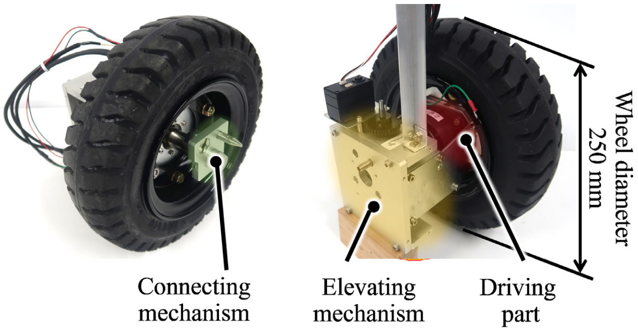


Fig. 6. Scale model of proposed driving wheel unit

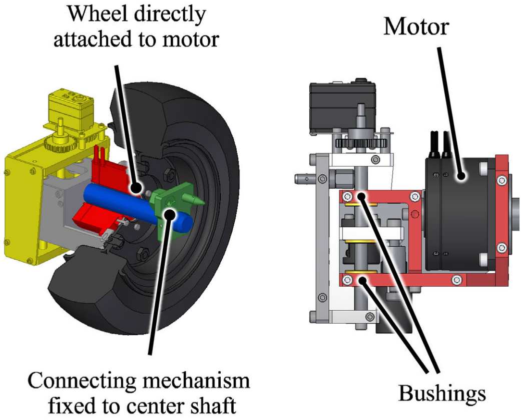


Fig. 7. Internal mechanism of the driving wheel unit

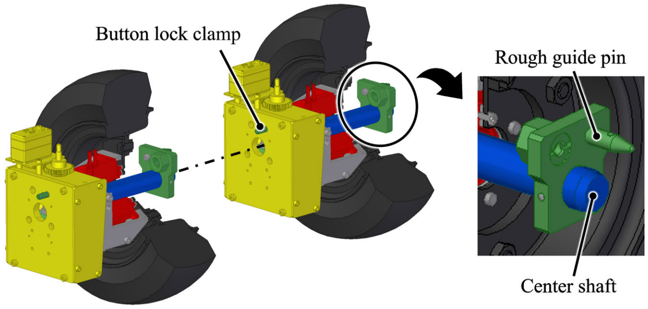


Fig. 8. Design of the connecting mechanism

V. TRACTION EXPERIMENTS USING THE DRIVING WHEEL UNITS

Traction experiments are conducted using the developed scale model. The objectives are to demonstrate that traction force can be enhanced by attaching the proposed motor-integrated additive driving wheel units and controlling their wheel height.

A. *Design of the Experiment Course*

The experiment course is shown in Fig. 12, and its diagram is presented in Fig. 13. On this course, a single-side wheel vehicle runs along a horizontal linear slider. A vertical linear slider is placed between the vehicle body and the horizontal slider so that the vehicle weight is supported by the wheels. In the following, the side closer to the horizontal slider is

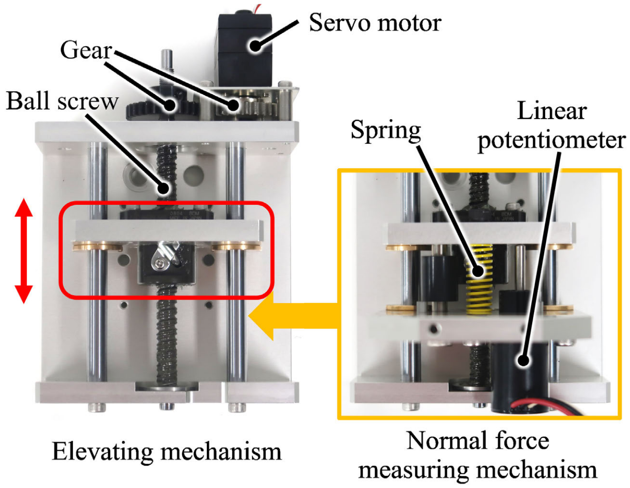


Fig. 9. Design of the elevating mechanism and the normal force estimation method

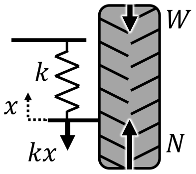


Fig. 10. Diagram of the normal force estimation mechanism

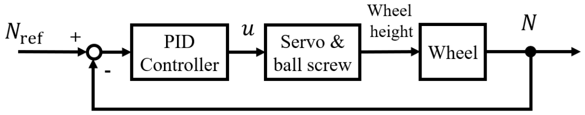


Fig. 11. Block diagram of the wheel height controller

referred to as the inner side, and the opposite side as the outer side.

In the experiments, the vehicle was tested on three types of surfaces: one paved road, and two unpaved road with soft surface and uneven surface, referred to as the soft road and the uneven road, respectively. The paved road is made of 9 mm thick plywood. As shown in Fig. 14, the soft road has a 20 mm thick urethane sponge sheet on top of the plywood, and covering it with polypropylene pellets of 3 mm to 4 mm in diameter. The uneven road has an 8 mm high step to a part of the plywood surface. Among the uneven road experiments, two experimental conditions were considered: one with the step located on the inner side and the other with the step on the outer side.

In addition, load cells were installed beneath the road surface to measure the normal forces actually applied to each driving wheel, thereby enabling the measurement of wheel loads exerted on the ground. Measurements from the load cells were used only for evaluating actual normal forces and were not utilized in the control of wheel height adjustment.

B. Experimental Conditions

The traction experiments were conducted under four road surface types (paved, soft, uneven with inner-side step, and uneven with outer-side step) and three levels of additional vehicle weight (0 kg, 2 kg, and 4 kg), resulting in $4 \times 3 = 12$ running conditions. For each of these running conditions, traction experiments were conducted under the following three driving conditions:

- One driving wheel unit
- Two driving wheel units without wheel height control
- Two driving wheel units with wheel height control

When using one driving wheel unit, the experiments were not conducted on uneven roads with an outer-side step because the wheel cannot use outer road in one driving wheel unit configuration. Additionally, when using two driving wheel units, pre-adjustment of wheel height was done before the experiments in order to initialize the wheel position. In total, 33 conditions were tested, with three trials conducted for each, resulting in 99 trials overall.

In this experiment, traction forces generated by the vehicle were compared across conditions. To determine the traction force in each trial, multiple traction runs were performed while incrementally changing the traction load. The maximum traction load among successful traction run was defined as the traction force for that trial. The traction load was varied in increments of 0.8 N, and a traction run was considered successful if the vehicle reached the 1100 mm point of the experiment course. Specifically, if the vehicle succeeded in traction run with a load of x N but failed with a load of $(x + 0.8)$ N, then the traction force for that trial was defined as x N. Fig. 15 shows sequential snapshots of the traction experiment.

C. Results and Discussion

For each road surface type, graphs were created with the experimental conditions (additional vehicle weight and driving configuration) on the horizontal axis and traction

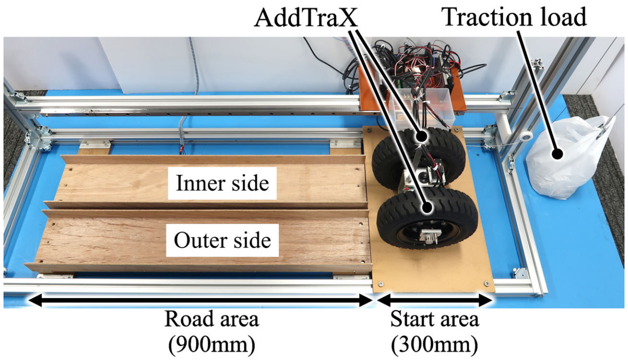


Fig. 12. Overview of the experiment course

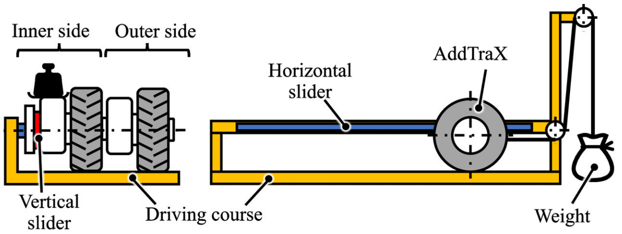


Fig. 13. Diagram of the experiment course

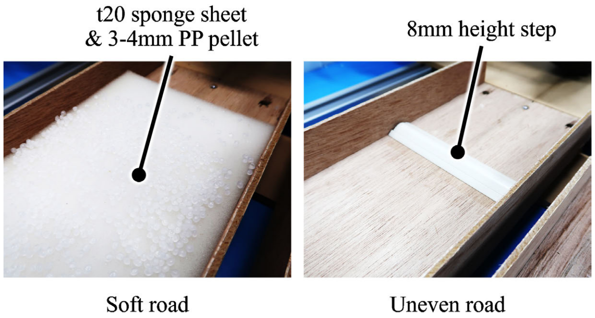


Fig. 14. Surface of the soft road (left) and the uneven road (right)

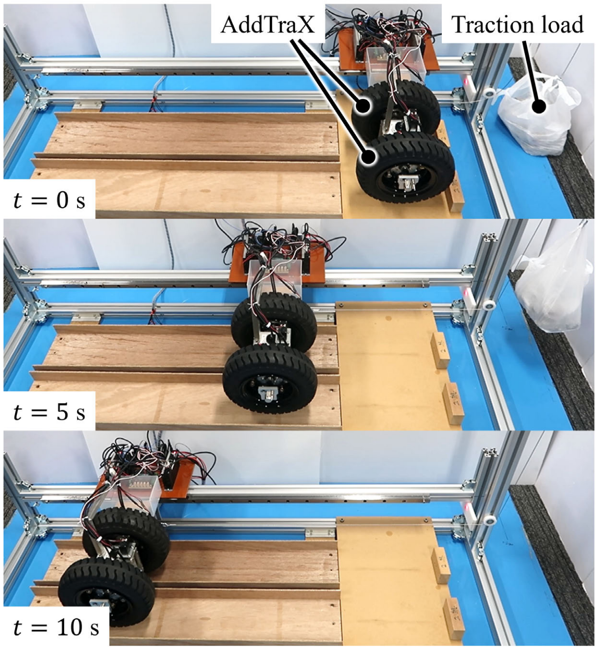


Fig. 15. Traction experiment with driving wheel units

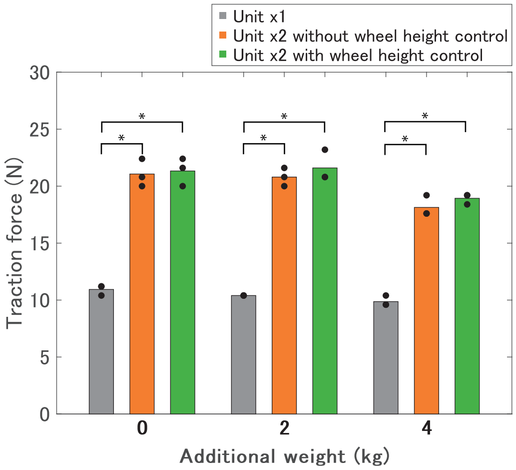


Fig. 16. Traction force on paved road (* :$p < 0.01$)

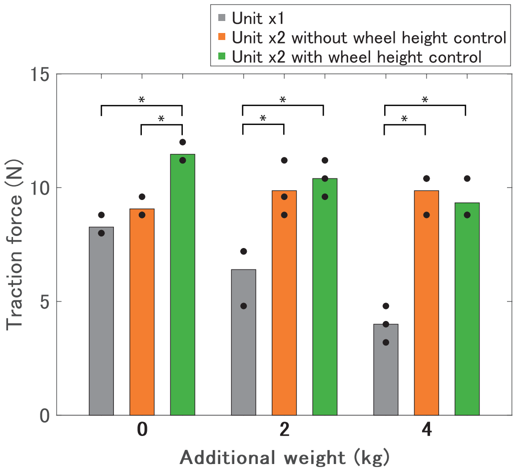


Fig. 17. Traction force on soft road (* :$p < 0.01$)

force on the vertical axis (Fig. 16, 17, 18 and 19). For each condition, the traction forces obtained in the three trials are plotted as black dots, and the average value is represented by the height of the bar. The data were assumed to follow a normal distribution, and Student's t-test was employed to evaluate statistical significance.

1) Paved Road: The experimental results on the paved road are shown in Fig. 16. When additional driving wheel units were attached, the traction force had statistically significant increase to approximately 1.9 times, 2.0 times, and 1.8 times that with a single unit under the conditions of $0\,\mathrm{kg}$, $2\,\mathrm{kg}$, and $4\,\mathrm{kg}$ of additional vehicle weight, respectively. On the other hand, for all weight conditions, traction force with wheel height control during operation showed no statistically significant difference compared to that without height control ($0\,\mathrm{kg}$: $p = 0.80$, $2\,\mathrm{kg}$: $p = 0.44$, $4\,\mathrm{kg}$: $p = 0.25 > 0.05$). These results cannot indicate that wheel height control during operation contributes to traction enhancement on paved roads. This is because the normal forces applied to each wheel remain relatively stable during operation on paved roads. Therefore, on paved roads, pre-adjustment of wheel height before operation is sufficient to enhance traction, and wheel height control during operation is unnecessary.

2) Soft Road: The experimental results on the soft road are shown in Fig. 17. Under the $0\mathrm{kg}$ additional weight condition, traction force with wheel height control was significantly greater than that without control ($p = 0.003 < 0.01$), increasing by a factor of 1.2. This result suggests that, on soft roads, variations in the normal forces acting on the wheels during operation were mitigated by wheel height control. On the other hand, under the $2\,\mathrm{kg}$ and $4\,\mathrm{kg}$ additional weight conditions, no statistically significant difference in traction force was observed between cases with and without wheel height control ($2\,\mathrm{kg}$: $p = 0.56$, $4\,\mathrm{kg}$: $p = 0.71 > 0.05$). It is considered that as vehicle weight increased, the wheels sank deeper into the soft surface, thereby reducing variations in normal force across wheels, and this diminished the effect of wheel height control. These findings indicate that on soft roads, wheel height control during operation contributes to traction enhancement when the vehicle weight is light.

3) Uneven Road: The experimental results on the uneven road are shown in Fig. 18 (the step on the inner side) and

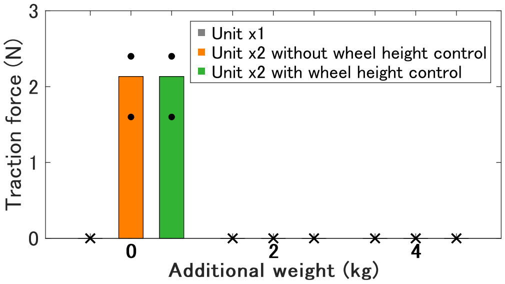


Fig. 18. Traction force on uneven road (step on inner side)

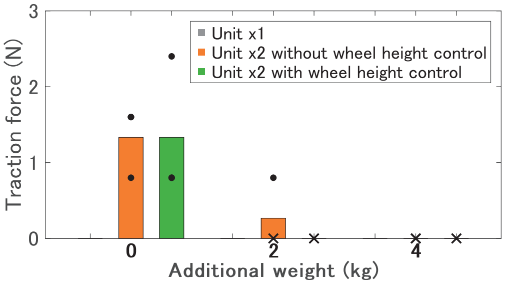


Fig. 19. Traction force on uneven road (step on outer side)

in Fig. 19 (the step on the outer side). For the outer-side step condition, the single-unit configuration is not displayed because it was not conducted. Additionally, trials in which the vehicle failed to pass over the step, even with zero traction load, are indicated by crosses at the 0 N position. In all cases, traction using a single driving wheel unit failed. However, under the 0 kg additional weight condition, traction was successful when an additional unit was attached. This suggests that attaching the additional driving wheel units improves the traction capability and enables the vehicle to climb over the step.

On the other hand, even in conditions where traction was successful, no statistically significant difference was observed between cases with and without wheel height control ($p = 1.00 > 0.05$). Furthermore, under the 2 kg and 4 kg additional weight conditions, traction failed in most trials even with an additional wheel unit. This is likely because the torque required to climb over the step exceeded the motor's output capability, preventing the effect of wheel height control from appearing. Since the experiments were conducted with single-side wheels only, additional resistance was generated by the vertical slider supporting the vehicle, and increased the torque required to climb over the step, as illustrated in Fig. 20. This is the limitation of this experiment, and it arises from the single-side configuration. Therefore, future work should include experiments using both sides of the wheels to more closely approximate actual vehicle operation.

4) Effect of Wheel Height Control: Time-series graphs of vehicle position, estimated normal force, and measured reference normal force over operation time were created. Fig. 21 shows an example without wheel height control, and Fig. 22 shows an example with wheel height control. The experimental condition of these examples is the soft road with 0 kg additional vehicle weight, where the wheel height control enhanced the traction force. In each figure, the top panel shows vehicle position, the middle panel shows estimated normal force, and the bottom panel shows measured reference normal force. The estimated normal forces were obtained from the normal force estimation methods installed in each wheel unit, while the measured reference normal forces were obtained from load cells placed beneath the road area. Note that before the vehicle reached the road area with load cells, the measured reference normal forces remained close to 0 N on the graphs.

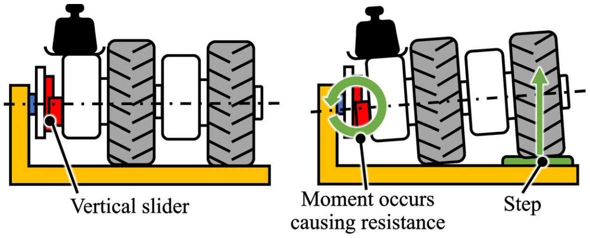


Fig. 20. Resistance around vertical slider

TABLE I

ABSOLUTE ERROR OF THE NORMAL FORCE ESTIMATION METHOD

Wheel height control	Side	Mean (%)	Maximum value (%)
Without	Inner	20.6	31.2
	Outer	12.6	21.3
With	Inner	16.7	24.1
	Outer	15.9	22.1

To verify the effect of wheel height control on normal force equalization, the absolute difference of measured reference normal forces between inner and outer wheel was calculated at each time step, and its average and maximum values were obtained. Without wheel height control, the average was 13.6 N and the maximum value was 35.9 N. With wheel height control, the average was 4.6 N and the maximum value was 14.9 N. Thus, the average decreased by 67% and the maximum value by 58%, and the wheel height control was found to be effective in equalizing normal forces.

Furthermore, to evaluate the absolute error of the implemented normal force estimation method, the ratio of the absolute difference between estimated and measured reference normal forces to the measured value was calculated at each time step, and its average and maximum values were obtained. The results are summarized in Table I. The average estimation error across all conditions was 16.5%. Therefore, the mechanism with only concise mechanical components (a spring and a linear potentiometer) was found to be able to estimate normal forces with an absolute error better than 20%.

VI. CONCLUSIONS

This study proposed a novel tractor concept that enables a single vehicle to perform tasks requiring different levels of traction force. The main concept is to enhance traction force of the tractor by employing multiple motor-integrated additive driving wheel units (AddTraX) and attaching them according to the required traction. The required functions of AddTraX were identified to be manual attachment of driving

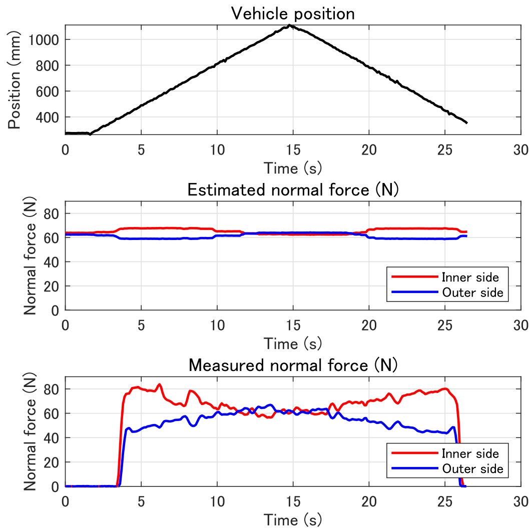


Fig. 21. Estimated and measured reference normal force without wheel height control

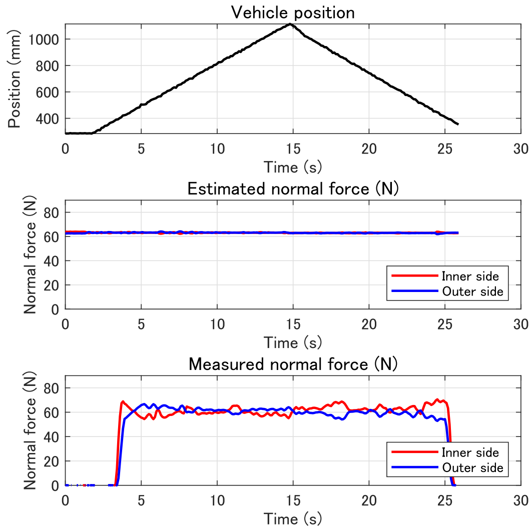


Fig. 22. Estimated and measured reference normal force with wheel height control

wheel units and wheel height control during operation. Then, a scale model that satisfies these required functions was designed and implemented. Furthermore, a control method was developed to equalize the normal forces among wheels by adjusting wheel heights during operation, based on estimated normal forces obtained from the normal force estimation methods installed in each unit. Traction experiments using the implemented scale model were conducted, and the feasibility of the proposed approach was verified.

The findings of this study are summarized as follows. (1) On paved roads, attaching an additional driving wheel unit increased traction force to approximately 1.9 times that with a single unit. Additionally, traction did not increase further when wheel height control was also applied, indicating that pre-adjustment of wheel height before operation is sufficient on paved road. (2) On soft roads, traction force was enhanced by attaching additional driving wheel units, and further improvement was achieved through wheel height control during operation when the vehicle weight was low. (3) On uneven roads, traction capability was improved by attaching additional units when the vehicle weight was low. However, no effect of wheel height control was observed. This is likely because the required torque to climb over step on road increased due to the single-side wheel configuration of the experiments. (4) The developed wheel height control effectively equalized the normal forces among wheels, reducing the average difference by 67% and the maximum difference by 58%. (5) The implemented normal force estimation method, consisting of a spring and a linear potentiometer, was able to estimate normal forces with an absolute error better than 20%.

As future work, traction experiments using both-side wheel configurations should be conducted to more closely approximate real vehicle conditions.

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