

[F] PhD Extended Abstract Form

RESEARCH ON A DIGITAL TWIN SYSTEM FOR FARM WORK UTILIZING AGRICULTURAL MACHINERY

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Extended Abstract

Introduction

The shortage of skilled agricultural labor and the rapid expansion of autonomous field operations are making robot tractors increasingly important to modern agriculture. Yet their development, validation and deployment still depend heavily on repeated field tests, which are costly, time-consuming, potentially unsafe, and often accompanied by additional soil compaction, fuel consumption and emissions. To alleviate these constraints, as much of the traditionally field-dependent workflow as possible could be transferred into cyber space, where tractor behavior, controllers and operation plans can be tested repeatedly, safely and efficiently before real deployment.

However, existing simulation approaches in cyber space have been developed mainly for general robotics or on-road vehicles, and therefore do not adequately represent key characteristics of agricultural tractor operation, including uneven terrain, pronounced tire sideslip, and asymmetric or non-linear steering behavior typically observed in agricultural tractors. These factors strongly affect motion reproduction and navigation accuracy, and have become a major bottleneck for the practical use of cyber space in agricultural machinery development and farmwork validation. At the same time, the role of cyber space should not end with offline pre-validation. Once the real tractor enters the field, a counterpart in cyber space can continue to create value by reflecting the current machine state, supporting remote monitoring, and enabling remote driving when unexpected situations arise. This, however, requires online communication, because modeling errors gradually accumulate during operation and the cyber model must be periodically corrected using the actual machine state to remain operationally relevant.

Against this background, this PhD research was organized into four studies. Study 1 established a high-fidelity cyber space framework for offline pre-validation of tractor motion and farmwork plans. Study 2 extended it to difficult field conditions through simulation of large sideslip. Study 3 introduced cyber-physical synchronization for online remote monitoring and remote driving, thereby evolving the framework into a digital twin system. Study 4 demonstrated its practical value through application studies on tractor design and farmwork planning.

Study 1. High-fidelity cyber-space framework for offline pre-validation of agricultural machinery navigation plans

The first study established the offline core of the proposed system, with the aim of reproducing the motion of a real robot tractor in cyber space under the same target path, target speed, and automatic steering controller as in physical space, so that navigation plans could be screened before field execution. The central contribution was a steering system simulator oriented for tractors, because the credibility of motion reproduction depended primarily on whether the cyber tractor could reproduce the asymmetric, non-linear, and mechanically constrained steering behavior of a real agricultural tractor. To address this bottleneck, a multi-stage steering mechanism was developed to reproduce dead time, continuous lag, steering rate limitation, and the hysteretic transition appearing under abrupt steering input changes. Two supporting modules were further introduced to reduce remaining mismatch: a sensor simulator that injected measured RTK-GNSS uncertainty into cyber space, and a tire interaction steering correction that reflected terrain-dependent turning characteristics on asphalt and soil surfaces. Combined with UAV-based terrain mesh model and a virtual Yanmar EG105 tractor using the same controller as the real one, the framework turned cyber space into a practical engineering tool for high-fidelity offline pre-validation, as illustrated in Fig. 1.

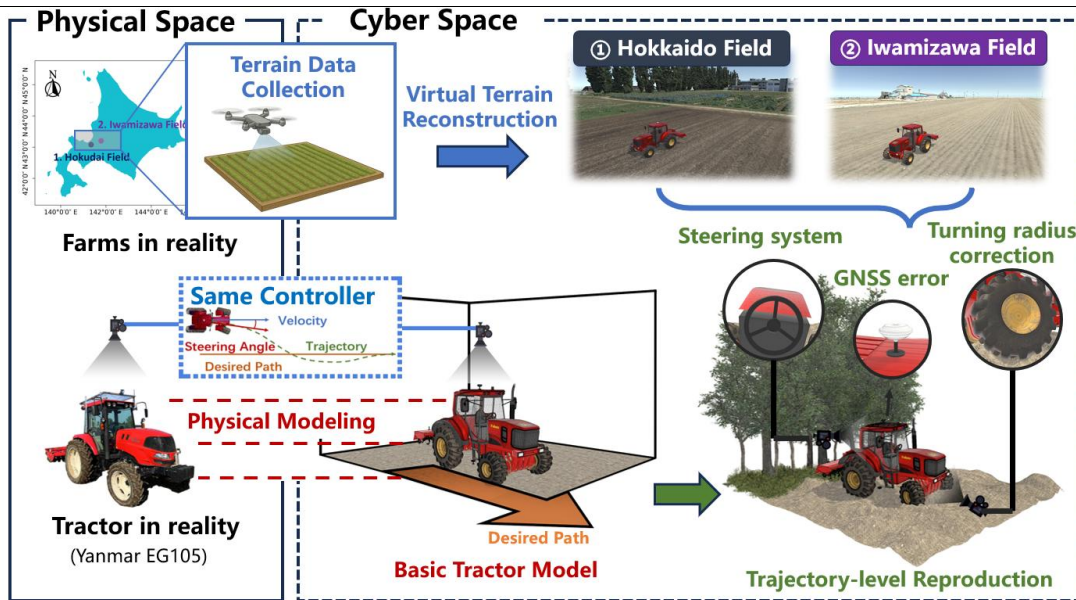


Fig. 1. Technology architecture of the proposed framework

The framework was validated through step offset response, zigzag, and real navigation experiments. Across the tests on soil conditions, the proposed method consistently outperformed a conventional first-order steering delay simulator, confirming that faithful steering behavior reproduction is essential for credible offline validation in agriculture. In the real navigation test, the average lateral errors of the cyber tractor on the two operation paths were 5.2 cm and 2.3 cm, close to 3.2 cm and 2.7 cm in physical space, demonstrating sufficient accuracy for practical offline pre-validation of navigation plans. The experiments also revealed the limitations of purely offline reproduction that discrepancies still accumulated during long operation, and steering correction alone became insufficient once strong non-linear sideslip emerged. These findings directly motivated the subsequent studies on large sideslip simulation and online cyber-physical synchronization.

Study 2. Non-linear dynamic model for sideslip simulation under difficult field conditions

The second study was motivated directly by a limitation identified in the first study: the reliability of the proposed cyber space framework degraded under wet or soft field conditions, where large sideslip became prominent. To address this problem, the study proposed a non-linear dynamic model specifically for agricultural vehicles in cyber space. Rather than relying on a highly parameterized model with limited practical tunability, it combined a simplified non-linear tire model with a sideslip angle estimation method to construct a lateral force estimation framework, which was then implemented in the Unity physics engine. The core significance of this study lies in extending cyber vehicle simulation from ordinary operation path following conditions to agricultural environments in which the relationship between lateral force and sideslip becomes strongly non-linear. As a result, the cyber tractor could reproduce not only normal motion states but also unstable behaviors caused by large sideslip, while still retaining the practical advantage of being adaptable through a relatively small set of tunable parameters.

The proposed model was validated through cyber pre-validation and real-world experiments on asphalt and muddy soil. While both the linear and non-linear models reproduced the asphalt road tests reasonably well, their difference became clear under muddy conditions, where large sideslip dominated tractor motion. In this case, the proposed non-linear model matched the real tractor much more closely, reproducing both the magnitude and temporal evolution of the navigation error. The average lateral error of the proposed method (0.163 m) was close to the real value (0.167 m), whereas the linear model underestimated it (0.122 m). These results show that the second study extended the scope of the cyber space framework from ordinary operation path following simulation to realistic tractor motion reproduction under difficult soil conditions, while retaining practical applicability through a limited number of tunable parameters.

Study 3. Online communication and cyber-physical synchronization for remote monitoring and remote driving

The third study addressed how the previously developed cyber-space framework could remain useful after offline pre-validation had been completed and the real tractor had already entered the field for actual operation. This shift in operating stage is important, because once field operation begins, cyber space is no longer needed only for advance validation of navigation plans, but also for real-time supervision of the ongoing task and for providing a virtual interface for human intervention when necessary. However, as already revealed in the first study, if the system relies on offline simulation alone, discrepancies between cyber space and physical space gradually accumulate during operation because of residual model mismatch, changing field conditions, and longitudinal drift. As a result, the cyber tractor progressively loses operational relevance. To overcome this limitation, the study introduced an online communication and synchronization subsystem that periodically corrected the cyber tractor using the real tractor state, thereby extending the proposed framework from offline pre-validation to cyber-physical operation support.



(a) Camera view from the real tractor



(b) Camera view from the digital twin system

Fig. 2. Online communication systems between the real tractor and the digital twin system

Field validation showed that the developed subsystem could suppress long-term error accumulation. More importantly, once this cyber-physical synchronization was established, the originally offline cyber framework evolved into a digital twin system that enabled not only real-time monitoring of the real tractor but also remote driving when combined with onboard camera views, as illustrated in Fig. 2. This capability also reduces supervision burden and creates the possibility for a single operator to remotely monitor multiple agricultural machines. It is particularly valuable under adverse operating conditions, such as low visibility or snow cover obscuring field boundaries, where farmers can still conduct remote machine operation with the assistance of the digital twin system.

Study 4. Applications and practical decision support enabled by the proposed digital twin system

The fourth study demonstrated how the proposed system can create direct value for both agricultural machinery development and farmwork planning.

On the robot tractor side, the proposed system enabled risky or costly validation tasks to be shifted from physical space into cyber space, where different vehicle configurations could be assessed rapidly and safely. Using the non-linear tractor model, the study examined tire selection and center-of-mass configuration, showing that rear tire grip is critical for steering stability, while center-of-mass placement affects turning stability and turning radius. These results indicate that the proposed system can support design decisions before prototype manufacture or costly field testing.

On the agricultural operation side, the proposed system was applied to pre-validate robot group size and cooperation strategy on a real 3D field model from Iwamizawa, Hokkaido. The results showed that simply increasing the number of robot tractors does not necessarily improve efficiency. For the same field, 9 tractors completed the task in 12 min 30 s, whereas 11 tractors required 13 min 10 s. The simulations also showed that, even with a fixed group size, strategy optimization can substantially improve performance. For a 5-tractor formation, optimizing waiting time before headland turning could reduce total operation time from 20 min 53 s to 17 min 18 s. These application studies show that the proposed system is not merely a simulation environment, but a practical decision support tool for machine design and farm operation planning, with clear potential to reduce field testing burden and improve operational efficiency under real agricultural conditions.

Final remarks concerning benchmarks and strength points of the Pellizzi Prize 2026

This PhD thesis belongs primarily to “Automation and Electronics”. It developed an original, practically oriented digital twin system for agricultural tractors by explicitly accounting for operating conditions and tractor motion characteristics, including a multi-stage steering system, sensor error injection, and non-linear sideslip simulation. The system supports offline pre-validation of farmwork plans as well as online remote monitoring and remote driving.

The transfer potential is clear because the full pipeline has already been demonstrated on a real farm field in Hokkaido, where different operation plans were pre-validated and compared for decision support. The expected benefits are more efficient planning, lower testing and operational costs, more labor-efficient supervision of multiple machines by a remote operator, safer work under difficult conditions, and reduced field damage and environmental burden, all of which can contribute to better productivity and returns for farmers.