Title	Research on a digital twin system on farm work utilizing agricultural machinery
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Degree Grantor	北海道大学
Degree Name	博士(農学)
Dissertation Number	甲第16591号
Issue Date	2025-09-25
DOI	https://doi.org/10.14943/doctoral.k16591
Doc URL	https://hdl.handle.net/2115/98201
Type	doctoral thesis
File Information	YU_Yue_abstract.pdf, 論文内容の要旨 https://creativecommons.org/licenses/by/4.0/

学位論文内容の要旨

博士の専攻分野名称：博士（農学）　　　　　　氏　名：YU Yue

学位論文題名

Research on a digital twin system on farm work utilizing agricultural machinery

（農業機械作業のデジタルツインシステムに関する研究）

Robotized agricultural machinery such as unmanned tractors, has been developed and plays an important role in reducing dependence on humans during agricultural production. However, several issues related with development and applications of robotized tractors raise concerns, including large demand of cost and time, damage to environment, and potential safety risks. Besides, work schedule optimization based on the developed robot tractors is also a problem derived from the above issues. Digital twin (DT) technology has emerged in diverse fields. Leveraging DT's advantages in cost, safety, and environmental sustainability, this study proposes a DT solution for agricultural machinery systems that could accurately replicate the motion state of a real tractor during planed operations in cyber space. The proposed DT system includes a detailed tractor model with side-slip simulation and remote controlling function. Experimental validation tests prove the effectiveness of the proposed DT system, and its potential abilities for both new agricultural machinery development and work schedule optimization.

1. Framework of the proposed DT system

Firstly, a preliminary digitization was conducted to import the real terrain and real tractor into cyber space, which was created by Unity software. The terrain data was collected by drone and converted to 3D models using 3D reconstruction techniques. Yanmar EG105 wheeled-type tractor was used as a phototype to construct a virtual tractor in cyber space, including key parameters and specifications of the basic model, along with the exact same controller used in the physical system. Then, subsystems reflecting detailed tractor motion characteristics were developed to implement the proposed DT solution. These subsystems include a global navigation satellite system (GNSS) error simulator, a steering system simulator, and a tire interaction simulator, designed to accurately replicate the dynamic motion of the target tractor. Finally, experimental results from both small-scale steering trajectory validation (step response

test) and large-scale work schedule validation (real navigation test) demonstrate the feasibility and effectiveness of the proposed DT solution on both asphalt and dry soil.

2. Non-linear improvement on the tractor model for side-slip simulation

When the peculiarities of the agricultural environment are more prominent, such as the soil becoming wetter and softer, the relationship between the tire lateral force and the tire side-slip angle will follow a non-linear tendency, which will cause the tire interaction simulator and basic tractor model to be less accurate. To solve this problem, a non-linear tractor model was proposed to make the simulation more practical to be applied under extreme agricultural environments, such as muddy field that are prone to cause large side-slips. First, a simplified non-linear tire model and side-slip angle estimation method were combined to make a lateral force-estimation method. Then the lateral force estimation was applied to the tractor model in DT system, to construct a non-linear dynamic model for agricultural vehicles in cyber space. The validation tests of both cyber space and real-world experiments prove that, the proposed non-linear model has strong practicality and can maintain higher accuracy compared with traditional linear vehicle model especially under extreme agricultural environments.

3. Development of a remote controlling system through online communication

During the offline operation of the proposed DT system, errors caused by dynamic environmental changes may continue to accumulate. To ensure the accuracy of the DT system during a long period of operation, online communication subsystem was developed using Web socket programming. Additionally, a state error estimation method is applied to compensate the communication latency as much as possible. The results from real-time field experiments together with simulation validates the stability and accuracy of the developed communication system.

4. Potential applications of the proposed DT system

To investigate the abilities of the proposed DT system in practical tasks related with agricultural machinery, validations for potential applications were conducted in cyber space. In general, the applications of the proposed DT system can be divided into two categories: (1) For robot tractor, and (2) For agricultural operation. For robot tractor, the proposed DT system was utilized to explore the optimal design of different combinations of tire parameters and center of mass positions. For agricultural operation, pre-validation examples are given to show the potential of the proposed DT system in work schedule optimizations for both tractor numbers and operation strategies.