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Experimental Validations of a Digital Twin Model for Underwater Tracked Vehicle

Jong-Boo Han[1,2], Sang-Jin Lee[2], Yeongjun Lee[1], Daegil Park[1,2] and Tae-Kyeong Yeu[1]

I. INTRODUCTION

Digital twin technologies are increasingly being adopted in robotics to enable model-based design, control development, and system-level performance evaluation. In underwater robotics, digital twins are particularly valuable due to the high cost, limited accessibility, and operational risks associated with real-world experiments. A reliable digital twin can significantly reduce experimental effort by enabling simulation-based testing and controller tuning prior to deployment.

However, developing accurate digital twins for underwater robotic systems remains challenging. In particular, tracked underwater robots operating on the seabed are subject to complex interactions involving track–ground contact, hydrodynamic forces, and vehicle dynamics. These interactions introduce nonlinear and environment-dependent behaviors that are difficult to model and validate. As a result, many existing studies rely on simplified models or lack sufficient experimental validation, limiting their practical applicability.

In this work, we present an experimental validation of a digital twin model for the CPOS ROVER, a tracked underwater robotic platform. The proposed digital twin is based on a high-fidelity multibody dynamics model that captures track–ground interaction and underwater external forces. To validate the model, water-tank experiments are conducted using a vision-based motion tracking system, and the simulation results are quantitatively compared with experimental data. The results demonstrate strong agreement at the position level, confirming the effectiveness of the proposed digital twin for representing tracked underwater locomotion.

II. DIGITAL TWIN MODEL

The digital twin of the CPOS ROVER is designed to reproduce its locomotion behavior under seabed contact conditions, as illustrated in Fig. 1. The model is constructed based on a high-fidelity multibody dynamics (MBD) framework, enabling the representation of the robot's mechanical structure and motion dynamics.

As shown in Fig. 1, the digital twin integrates key physical components, including track–ground interaction, hydrodynamic effects, and vehicle dynamics. The track–ground interaction model captures normal reaction forces and traction characteristics, which are essential for describing locomotion on the seabed. Hydrodynamic forces such as drag and buoyancy are also incorporated to reflect underwater operating conditions.

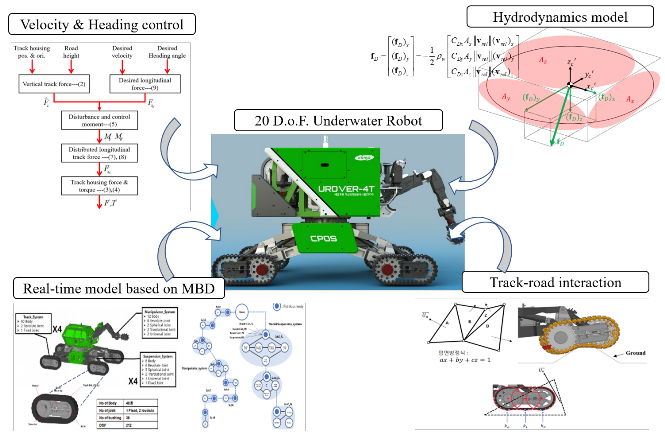

Fig. 1. Overview of the digital twin framework for the CPOS ROVER.

The digital twin is driven by the same input conditions as the physical system, allowing direct comparison between simulated and experimental trajectories. This enables quantitative validation of the model in terms of position and motion behavior.

III. EXPERIMENTAL VALIDATION

To validate the accuracy of the proposed digital twin, water-tank experiments were conducted using the CPOS ROVER, as shown in Fig. 2. The experimental setup includes a vision-based motion tracking system in which visual markers are mounted on the robot to enable precise position measurement, while an external camera system installed above the tank captures the robot motion during operation.

In addition to the vision-based tracking system, the CPOS ROVER is equipped with onboard sensors for state estimation. A Doppler Velocity Log (DVL) and a fiber optic gyroscope (FOG) are installed on the lower part of the robot body, and their measurements are fused to estimate the robot's position and attitude based on a dead-reckoning inertial navigation scheme.

The experimental environment was designed to emulate realistic seabed conditions. Bathymetric data obtained from an offshore region near Jeju Island were used, and a representative section of the terrain (3 m $\times$ 12 m) was reconstructed in

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[1]Korea Research Institute of Ships and Ocean Engineering, Korea
[2]Department of Ships and Ocean Engineering, University of Science and Technology, Daejeon, Republic of Korea

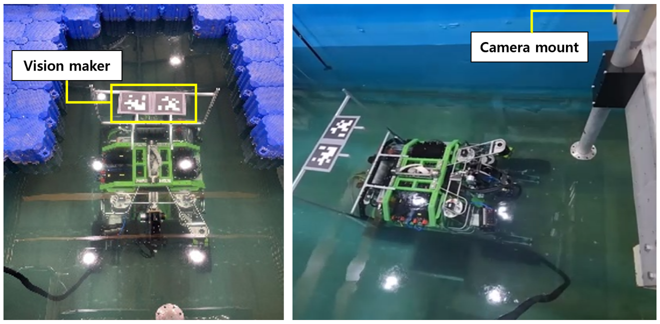

Fig. 2. Experimental setup for digital twin validation.

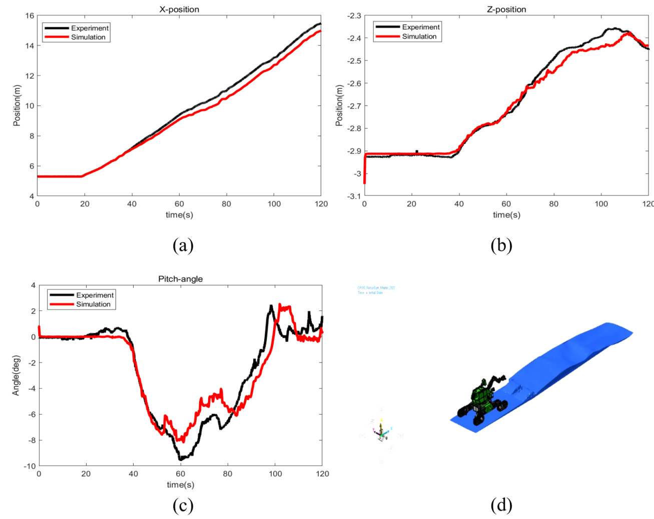

Fig. 3. Comparison between experimental and simulation results: (a) X-position, (b) Z-position, (c) pitch angle, and (d) simulation snapshot on reconstructed terrain.

the water tank. The same terrain profile was also incorporated into the digital twin model, ensuring consistency between simulation and experimental conditions. In the experiments, the robot traversed the constructed terrain in both forward and backward directions over a total distance of 12 m at an approximate speed of 0.25 m/s. The same input commands were applied to both the physical system and the digital twin model to maintain consistent test conditions. The robot motion was recorded using the vision-based tracking system, which serves as ground-truth data for validation.

The recorded trajectories were compared with the simulation results in terms of position and overall motion behavior, allowing quantitative evaluation of the digital twin's capability to reproduce real-world locomotion under seabed contact conditions.

IV. Results

The comparison between experimental and simulation results is presented in Fig. 3, including the time histories of X-position, Z-position, and pitch angle during traversal of the reconstructed seabed.

As shown in Fig. 3(a), the simulated X-position follows the experimental trajectory closely, with only small deviations over the full travel distance, indicating that the overall forward motion is well reproduced.

In Fig. 3(b), the Z-position captures the terrain profile and general elevation trend, although minor discrepancies appear in some regions, likely due to modeling limitations.

Fig. 3(c) shows the pitch angle variation, where both results exhibit similar trends corresponding to terrain slope, despite some differences in peak values and transient responses.

Overall, the digital twin reproduces the real-world locomotion behavior reasonably well under seabed contact conditions. Quantitatively, the cross-correlation function (CCF) indicates about 97% agreement at the position level and 85% at the velocity level.

V. Conclusion

This paper presented the experimental validation of a digital twin model for the CPOS ROVER operating under seabed contact conditions. The proposed model was evaluated through water-tank experiments using a vision-based tracking system, demonstrating strong agreement between simulation and experimental results. Quantitative analysis confirmed that the digital twin achieves high accuracy at the position level, highlighting its effectiveness for representing tracked underwater locomotion. The results suggest that the proposed framework can be effectively utilized for controller development and simulation-based performance evaluation.

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