

# Operational Reliability and Tip-over Prevention for Mobile Manipulators in High-Radiation Environments

Jaehee Park<sup>a</sup>, Jinyi Lee<sup>b</sup>, Jongwon Park<sup>b\*</sup>

<sup>a</sup>University of Science & Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea

<sup>b</sup>Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 04535, Republic of Korea

\*Corresponding author: [jwpark@kaeri.re.kr](mailto:jwpark@kaeri.re.kr)

\***Keywords** : Mobile Manipulator, Tip-over Prevention, Zero Moment Point, Deep Reinforcement Learning

## 1. Introduction

Maintenance tasks in nuclear power plants, such as nuclear fuel replacement, radioactive waste handling, and facility decommissioning, are performed in environments with a constant risk of high-level radiation exposure. To fully guarantee worker safety, the introduction of high-degree-of-freedom mobile manipulators to replace human workers is essentially required[1], [2].

However, a critical tip-over accident can occur when a robot loses its balance while handling heavy nuclear fuel or operating shielding materials in an actual nuclear environment. If the robot tips over, fails to recover on its own, and becomes incapable of performing its mission, human workers must ultimately be re-inserted into the high-radiation zone to complete the interrupted task and retrieve the robot. This completely defeats the fundamental purpose of deploying robots, which is to secure worker safety through human replacement. Therefore, absolute balance maintenance capability for robots in nuclear environments is not merely an improvement in control performance, but a core requirement directly linked to the success or failure of the task. This paper analyzes the latest trends in balance control technologies to prevent the tip-over of robots working in high-radiation environments and suggests future directions for control system development.

## 2. Robot Tipping in High-Radiation Environments

Tasks within nuclear facilities involve grasping and precisely manipulating heavy objects. A mobile manipulator, which combines a multi-joint manipulator on a mobile base, inherently possesses a high Center of Gravity (CoG). The moment the robotic arm lifts a heavy object and reaches outside its operating radius, the CoG of the entire system rapidly shifts toward the boundary of the Support Polygon, generating a strong tip-over moment. When irregular floor bumps or unexpected external collisions are added to this, the robot instantly falls into a state of dynamic instability[3].

## 3. Advances in Robot Balance Control

As the kinematic design capabilities of robots advance, tip-over prevention technology is evolving from merely

maintaining static stability to actively balancing by generating real-time dynamic trajectories.

### 3.1 ZMP-Based Stability Control

Many early and commercialized systems adopt conservative control methods that restrict the Zero Moment Point (ZMP) or CoG to remain within the support polygon. The fundamental concept of ZMP is to determine the point on the ground where the horizontal tipping moment becomes zero. For a multi-link robotic system, the ZMP coordinate  $x_{zmp}$  in the sagittal plane is generally calculated as follows.

$$x_{zmp} = \frac{\sum_{i=1}^n m_i(z_i+g)x_i - \sum_{i=1}^n m_i\ddot{x}_i z_i}{\sum_{i=1}^n m_i(\ddot{z}_i+g)} \quad (1)$$

where  $n$  is the number of links,  $m_i$  is the mass of link  $i$ ,  $(x_i, z_i)$  represents the center of mass coordinates of the link,  $\ddot{x}_i, \ddot{z}_i$  denotes its acceleration, and  $g$  is the gravitational acceleration[4].

This formula-based method calculates the expected moment when the manipulator moves and limits the operation speed and payload capacity so as not to exceed the boundary of the support polygon. However, calculating these dynamics accurately in real-time under unexpected disturbances is computationally intensive. Furthermore, these static approaches often assume flat terrain, which limits their application in actual nuclear environments where unpredictable irregularities such as steps or cables exist, significantly degrading the robot's work efficiency.

### 3.2 Dynamic Balancing with Deep RL

Recently, to overcome the limitations of complex analytical formulas and respond to unexpected disturbances in real time, dynamic balance control research utilizing Deep Reinforcement Learning (DRL) has become mainstream. In particular, technology that controls balance by configuring the entire robot system as an integrated single agent is gaining attention [5].

As conceptually illustrated in Fig. 1, this approach does not decouple the movement of the mobile base from the multi-joint movements of the manipulator. Instead, to compensate for the rapid CoG shift caused by handling heavy objects, the neural network policy observes the

state and generates optimal whole-body control strategies in real time. The moment the robot is about to fall, the RL agent instantaneously modifies the target trajectory of each joint and leverages the motion of the robotic arm to actively stabilize the base, keeping the CoG within the support polygon. This enables the prevention of tip-overs during high-speed, high-payload dynamic tasks, which is challenging with traditional mathematical control methods.

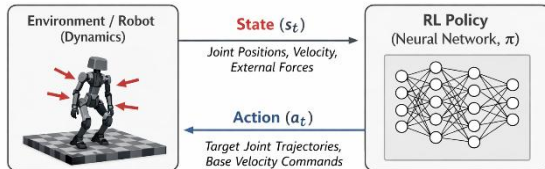


Fig. 1. Conceptual framework of DRL for dynamic balancing

### 3.3 Physics-Based Sim-to-Real Transfer

Due to the environmental constraints of high radiation, it is practically impossible to repeatedly test numerous tip-over situations on actual hardware. Therefore, the latest research trends actively utilize advanced 3D physics engine-based simulator environments, such as Isaac Sim, where dynamic laws like friction, gravity, and inertia tensors are precisely simulated. The robot experiences tens of thousands of heavy payload manipulation and near-tip-over scenarios within the virtual environment, learning the joint trajectory control policy to maintain balance through the single-agent RL algorithm. Subsequently, Sim-to-Real technology, which transfers the learned policy to actual hardware, is establishing itself as an essential process in the development of tip-over prevention systems for nuclear applications[6].

## 4. Conclusions

Robot tip-overs in nuclear environments lead to the re-insertion of human personnel, a critical issue that undermines the fundamental purpose of unmanned operations. This paper reviewed the trends in tip-over prevention and balance control technologies to ensure the safety of robots for high-radiation environments. Moving beyond conventional conservative static control methods like ZMP, which have limitations in unstructured terrain, recent technology is advancing toward actively maintaining balance by generating compensatory trajectories for each joint in real time through single-agent reinforcement learning. Future research must focus on advancing robust trajectory control algorithms capable of withstanding extreme disturbance situations specialized for nuclear environments, validated using high-fidelity physics simulators.

## ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(Ministry of Science and ICT)(No. RS-2022-00144468).

## REFERENCES

- [1] Y. Ou et al., "An overview on mobile manipulator in nuclear applications," ResearchGate, 2022.
- [2] H. Kwon et al., "Vision-Guided Robotic High-Torque Bolt Fastening for Nuclear Power Plant Maintenance," Transactions of the Korean Nuclear Society, 2025.
- [3] "Tip-Over Detection and Avoidance Algorithms as Stabilization Strategy for Small-Footprint and Lightweight Mobile Manipulators," ResearchGate, 2022.
- [4] Q. Huang and S. Sugano, "Stability control for a mobile manipulator using a potential method," Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 1994.
- [5] V. Vatsal and B. Purushothaman, "Reinforcement Learning of Whole-Body Control Strategies to Balance a Dynamically Stable Mobile Manipulator," IEEE Xplore, 2021.
- [6] J. Albardaner et al., "Sim-to-Real gap in RL: Use Case with TIAGo and Isaac Sim/Gym," arXiv preprint arXiv:2403.07091, 2024.