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AUTOMATED CATTLE INJECTIONS: A ROBOTIC AND DIGITAL TWIN APPROACH TO FEEDLOT EFFICIENCY

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INTRODUCTION

The adoption of robotics in agriculture is often hindered by the high cost and risk of unproven technologies. Digital twins offer a solution by enabling the virtual design, simulation, and validation of automated systems before physical deployment. This paper presents a digital twin framework in NVIDIA Isaac [1] for a robotic cattle vaccination system. Using a Detectron2 model for neck segmentation and a Proximal Policy Optimization (PPO) agent for control, we validate the feasibility of this approach. This simulation-first pipeline serves as a low-risk proof-of-concept for producers, demonstrating a pathway to scalable and safe automation [2].

MATERIALS AND METHODS

Our system architecture is a digital twin built in NVIDIA Isaac Sim, featuring CAD models of a cattle chute and a rigged 3D animal. We first validated our control framework using a simulated Franka Emika Panda arm before adapting it to a custom 6-DOF manipulator. Perception is handled by a fine-tuned Detectron2 model that processes simulated RGB-D camera input to segment the injection site. A control agent, trained with Proximal Policy Optimization (PPO), uses these coordinates to guide the arm. The agent's reward function promotes smooth and accurate motion. Performance was evaluated by measuring final positional error after training separate policies for 5, 10, and 15-second task durations.

RESULTS AND DISCUSSION

The PPO-trained agent achieved high-precision, sub-centimeter targeting in all test conditions (Table 1). Using the baseline Franka Emika Panda arm, the policy with a 10s-time limit yielded the lowest median error (0.456 cm), indicating an optimal balance of speed and precision. The 15s policy was the most consistent, with the lowest Median Absolute Deviation (MAD) of 0.063 cm. These results validate our simulation-first approach for optimizing control policies. Training separate policies for different time horizons provides operational flexibility and establishes a strong foundation for sim-to-real transfer.

Fig 1 The training environment in NVIDIA Isaac Sim, showing the digital twin of the robotic arm, cattle, and chute used to train the reinforcement learning agent

CONCLUSIONS

This work validates a simulation-first paradigm for de-risking agricultural robotics. Our digital twin in NVIDIA Isaac Sim provides an effective virtual proof-of-concept for an AI-driven vaccination system, establishing an efficient pathway from concept to commercialization. This research is a foundational step toward a modular platform for Precision Livestock Farming that aligns with Industry 5.0 principles, using automation to augment human skill, enhance safety, and improve animal welfare

REFERENCES

[1] Makoviychuk V et al. arXiv:2108.10470, 2021.
[2] Liu Y et al. IEEE Trans Ind Informatics 17(6): 4322–4334, 2021.

Table 1: *Performance of the PPO-trained agent with a Franka Emika Panda arm under 5 s, 10 s, and 15 s time limits. Reported are median positioning error (cm), 95% CI for the median (lower/upper), and median absolute deviation (MAD); n = 50 episodes per condition.*

Time constraint	Episodes (n)	Median error (cm)	Median 95% CI low	Median 95% CI high	MAD (cm)
5s	50	0.485	0.418	0.516	0.083
10s	50	0.456	0.419	0.524	0.083
15s	50	0.487	0.463	0.506	0.063