Dynamic Digital Twins for Adaptive Feed-Forward Control in CNC Robotics

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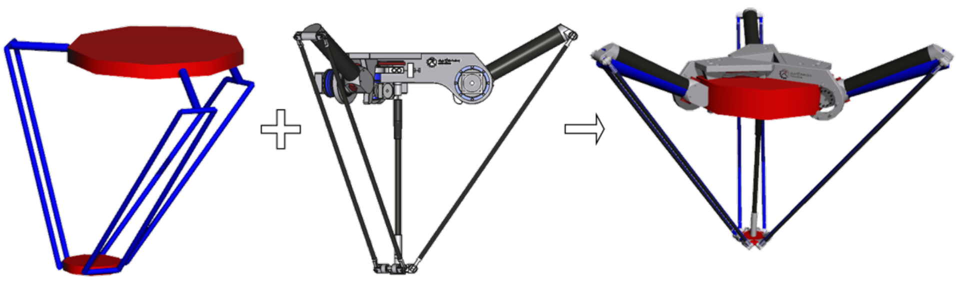

Figure 1: Digital Twin of the Delta Robot (right), consisting of kinematic model (left) and CAD model (center) used for collision detection and visualization.

The adoption of robotics has become increasingly essential for industries grappling with a shortage of skilled labor. Automation not only addresses workforce challenges but also provides significant economic advantages, as highlighted in [1] and [2]. Especially CNC-controlled pick-and-place and material handling applications demand high positioning accuracy, low tracking error, and adaptability to variable payloads and robot configurations. Traditionally, digital twin models used during virtual commissioning (VC) are discarded after deployment due to their limited physical fidelity. These models typically provide only logical and kinematic representations of the robot, offering basic collision detection via bounding box approximations but lacking the dynamic behavior needed for high-precision control in real-world operation.

In this work, we present an extended digital twin framework that upgrades these pre-existing virtual commissioning models by adding a fully parametric dynamic layer. The enhanced twin supports real-time model-based feedforward control and is capable of adapting to changes in payload and contact states during robot operation. This makes it possible to continue using the digital twin not only during early system integration but also as an active component of online control throughout the machine's lifecycle as previously shown in [3].

The dynamic models are generated in a script-based, modular fashion using the virtual commissioning platform, allowing users to easily adjust system parameters or switch between different robot configurations. As a proof of concept, a parallel delta robot is implemented (see Fig. 1). It serves as a foundational template, with the long-term goal of establishing a library of parametric robot models usable across different manufacturing systems. A key innovation in the presented method is the integration of a collision detection mechanism that transitions from a purely protective function to a source of real-time payload detection. Once a workpiece is grasped, the system calculates its geometric and inertial properties based on the object's shape and density. The resulting payload mass is then automatically incorporated into the robot's equations of motion, allowing the feedforward control to adjust its torque predictions accordingly.

This dynamic adaptation leads to a significant reduction in tracking error, especially in high-inertia cases where conventional control systems struggle due to unmodeled payload dynamics. The improvement is most evident during transitions between free motion and contact, such as during grasping or precise insertion tasks. Our approach demonstrates that digital twins need not be discarded post-commissioning; instead, by using the established interface from [4] they can be enhanced and maintained as part of the operational control infrastructure.

References

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