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Digital twin architecture and sim-to-real gap analysis of a material transfer system in a remanufacturing environment

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Abstract

This paper presents a digital twin architecture for a material flow system as well as experiments to determine the sim-to-real gap between virtual models and their real counterparts. The architecture comprises three layers, namely the physical/logical layer, the cyber layer as well as the descriptive layer. Virtual and real assets are able to communicate on the cyber layer by means of OPCUA and the Asset Administration Shell (AAS). The virtual models are implemented in a physics-based simulation environment and allow the reuse of all control and application layer software modules of their real counterpart. In addition, the sim-to-real gap between a selected asset, namely the *Transfer Unit* is analyzed by means of a collision analysis of the material transfer of simple shaped objects. The results show similar behavior of the real and the virtual models. However, more effort is needed to accurately model the meshes of the collision elements to ensure realistic results.

Keywords: Digital Twin; Sim-to-Real; Remanufacturing; Intralogistics; Material Handling

1. Introduction

Remanufacturing systems, and disassembly systems in particular, are characterized by a large variety of different components (parts, sub-assemblies or full assembled products) that need to be handled and transported on their individual route through the system. All of these components have varying physical attributes like shape, size, weight, surface quality or stiffness [1]. The Agiprobot project investigates methods to deal with the uncertainty caused by products and processes. In this context, the material flow system must be able to transfer a wide variety of objects. In contrast to conventional material flow systems in linear production, we assume limited knowledge about the object state. In order to deal with this uncertainty, much more intelligent and robust systems are necessary. Digital twins of intelligent, interacting resources promise to make an important contribution to this. Digital twins rely on accurate virtual models which are used for prediction, monitoring or diagnosis functions. To be able to make decisions for the real system, the "sim-to-real"-gap between the virtual models and the real counterpart must be sufficiently small. In this paper, we present a digital twin architecture as well as experimental results to evaluate the sim-to-real gap between the virtual models and their real counterparts.

Recent reviews regarding digital twins (DTs) in the manufacturing domain show a growing research interest in the application of digital twins in logistics and material handling [2, 3]. With regards to the virtual model used in their DT architecture, the majority of publications use Discrete Event Simulations (DES) and operate on plant level rather then on a specific material transfer between two systems. Only a few publications mention the use of physics-based simulations for a material transfer. Zheng et. al. present the digital twin for a welding production line. However, the virtual models are mainly used for monitoring and visualization rather then for forward simulation and optimization [4]. Glatt et. al. describe a DT based material transfer system in which a physics engine is used to predict, monitor, and diagnose a physical material flow. The goal of the integrated physics simulation is to reduce physical disturbances during the interaction between the workpiece and the material transfer system [5].

In the remainder of this paper, we firstly introduce the developed DT architecture (Section 2). Afterwards we analyze the sim-to-real gap between the physics-based virtual models and their real-world twins by means of collision simulation (Section

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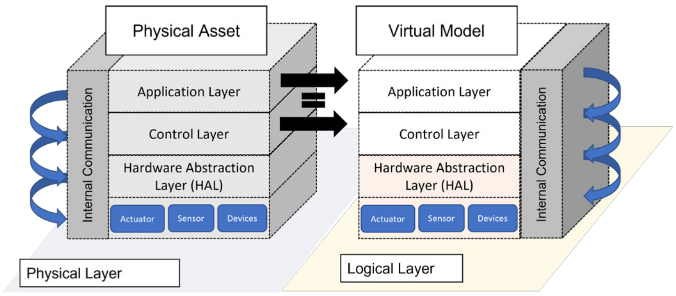


Fig. 1: Layered abstraction of a smart physical asset with internal communication and its virtual model sharing the identical control and application layer.

3.2) and sensor modeling (Section 3). Finally, we summarize and conclude the paper (Section 4).

2. System architecture overview

The presented material transfer system is an integrated part of the intralogistics of a fluid automated production system with the overall goal of achieving high automation ensuring high flexibility and adaptability [6]. In general, the system is a Cyber Physical Production System (CPPS), which includes loosely connected, encapsulated assets that share information and interact to achieve a higher level production goal. All assets share common characteristics such as smartness, connectedness and responsiveness to internal and external changes [7]. Figure 1 illustrates the layered model of a smart physical asset which are resources with a material existence. They include static and dynamic hardware components as well as software components ranging from embedded components on the hardware abstraction layer (HAL) to control and application components. The physical asset typically uses an internal communication framework or middleware to connect the application layer, control layer and HAL, e.g. the Robot Operating System (ROS), while communication between actuators, sensors and devices with the HAL is typically done using fieldbus protocols.

2.1. Assets of the material transfer system

We distinguish between two types of assets: physical assets (smart and not smart) and logical assets which include the virtual models of the physical assets [8].

2.1.1. Physical Assets

In the case of the presented material transfer system here, we consider three physical assets, namely the *Transfer Module* (TM), the *Transfer Unit* (TU), and the *Object* to be transferred. Figure 2 shows all three assets during a material transfer operation. The TU consists of two separately driven conveyor belts and two light sensors that mark the end of each belt. The TM consists of a liDAR-based autonomous mobile robot (AMR) as a moving platform, a mounted TU and a vision system based on an actuated RGB-D camera. On the physical shop-floor level, the production system is organized in different *Stations*, each consisting of at least one *Station Module* which can mount up to four *Elementary Units*. For more information on the assets and the production system architecture, see [6, 9, 10]. The goal of the presented material transfer system is to

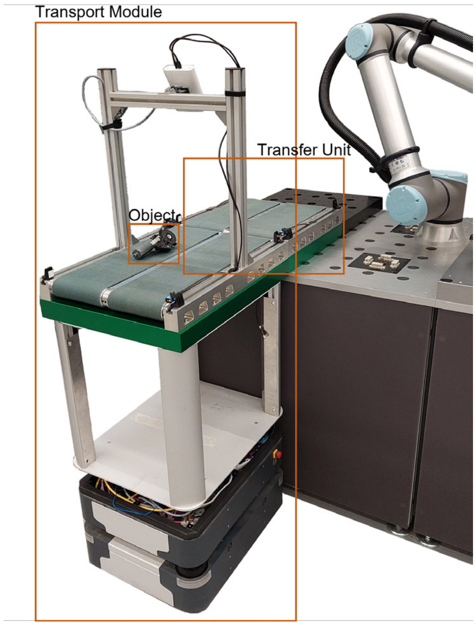


Fig. 2: Physical assets of the material transfer system

- transfer objects with uncertain information about the objects' characteristics,
- from a TM to a TU and vice versa,
- while updating and exchanging object information.

2.1.2. Logical Assets

Logical assets include non-material entities, usually software applications, that interact with other assets (from all layers). In the case of the material transfer system presented, the logical assets currently include a GUI for triggering and monitoring material handling operations. In the future, advanced analysis tools will be added to provide decision support based on the DT architecture.

For each physical asset, we created a virtual model in NVIDIA Isaac Sim [11], a physics-based robotics simulation platform with advanced rendering capabilities. By having a simulation environment that covers the whole material transfer system, we are able to conduct large-scale virtual experiments with unknown or physically unavailable objects. The virtual models attempt to mirror the physical assets as closely as possible. This includes not only the physical mapping, but also the mapping of the internal communication architecture. By ensuring the same interfaces, the virtual models can use all software components of the application and control layer of the physical model, see figure 1.

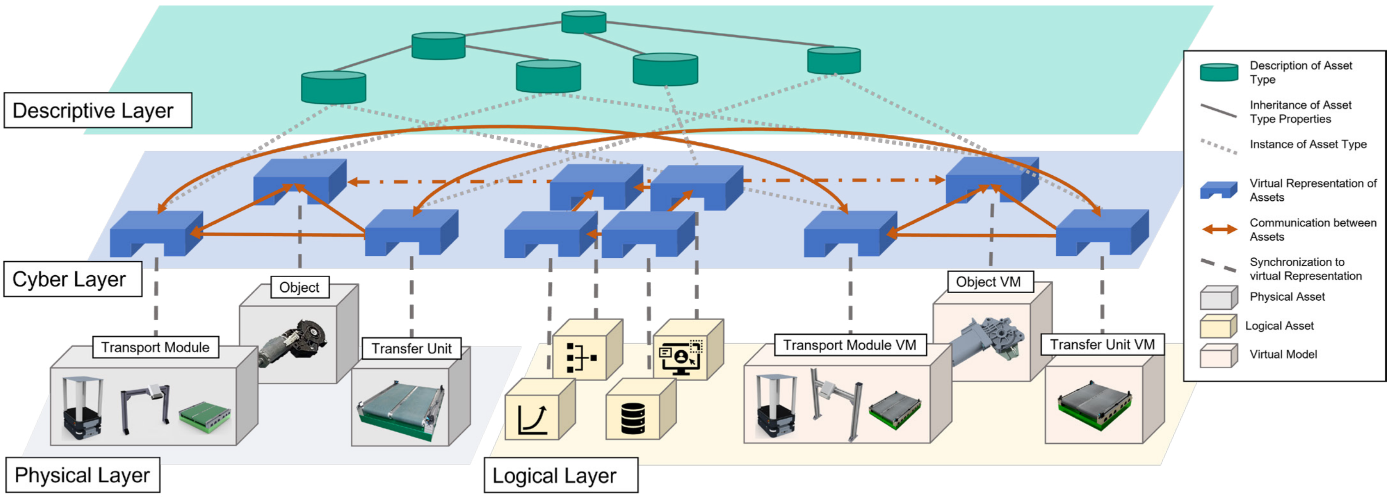


Fig. 3: Material transfer system architecture: physical and logical assets interact on cyber level based on their asset administration shells, inspired by [8]

2.2. Digital twin

One of the first mentions of the term *Digital Twin* appeared in a NASA roadmap where it was used as a synonym for an integrated multiphysics, multiscale simulation of a system with the goal of mirroring the real system in the best possible way [12]. Over the years, there have been many different definitions as well as an increasing number of reviews that try to give a clear overview of the existing ones. Van der Horn et. al. ,e.g., summarizes 46 different definitions and proposed a generalized one that describes DT as a

> "virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual system" [13].

Figure 3 illustrates the DT architecture of the material transfer system. The physical layer includes the TM, the TU and the object being transferred. Similar to other *Elementary Units* in the production system, see [6], they are considered as loosely coupled, encapsulated assets that are able to interact and exchange information. The logical layer includes the virtual models of the physical assets ass well as additional non-material assets as described in section 2.1.2. The cyber layer holds the virtual representations of all assets in the form of Asset Administration Shells (AAS), a german concept in Industry 4.0 that describes the digital identity of an asset and contains relevant information such as properties, states and relationships with other assets [14].

Figure 4 shows the implementation of the AAS for the TM and TU in more detail. Both assets host their own OPC UA server that uses the AAS data model which is mapped to an OPC UA information model by the OPC 30270 specification. The AAS of the *Transport Module* consists of three submodels. The "TransferUnit" submodel contains real-time data related to the sensors and actuators of the mounted TU, currently detected and tracked objects as well as methods to set the conveyor speeds. In the case of the stationary TU, the "TransferUnit" submodel additionally provides a docking and reservation service for any connecting TM. The "TransferControl" submodel allows to start, stop and monitor a material transfer operation. Finally, the "MobileBase" submodel contains data and methods related to the AMR. Internally, both systems use ROS at their middleware. Interoperability on the cyber layer is further ensured by a system-wide knowledge graph on the descriptive layer, which is discussed in [10].

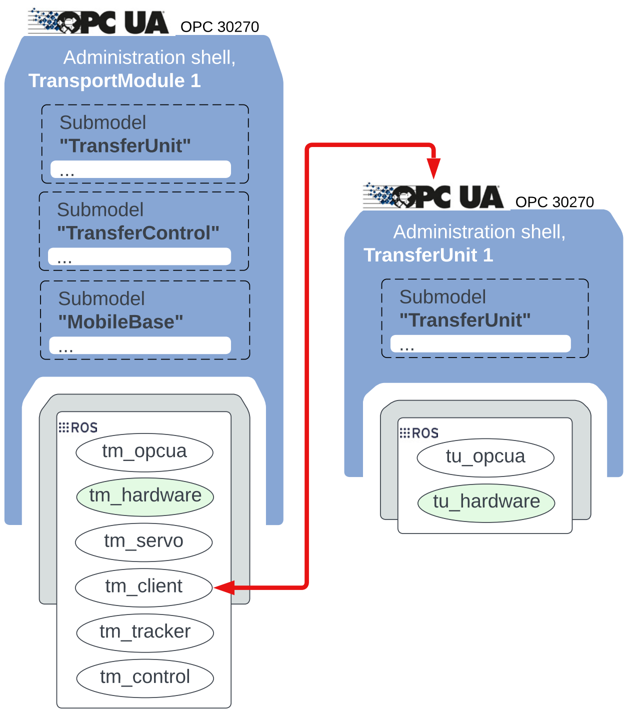


Fig. 4: AAS architecture and relevant ROS nodes of the *Transport Module* and a *Transfer Unit*

A digital twin is characterized by a bidirectional automatic data flow between the physical asset and its digital counterpart [15]. However, a simple virtual representation that is continuously updated is not enough. To create real value, additional logic is required to enable core functions of a DT [5, 12]:

- **Prediction**: An operation is performed on the DT prior to the implementation on the real system.
- **Monitoring**: Continuously predict, e.g., the future state of a system or the success of a current operation.
- **Diagnosis**: If the real system fails, the DT can be used to diagnose the cause.

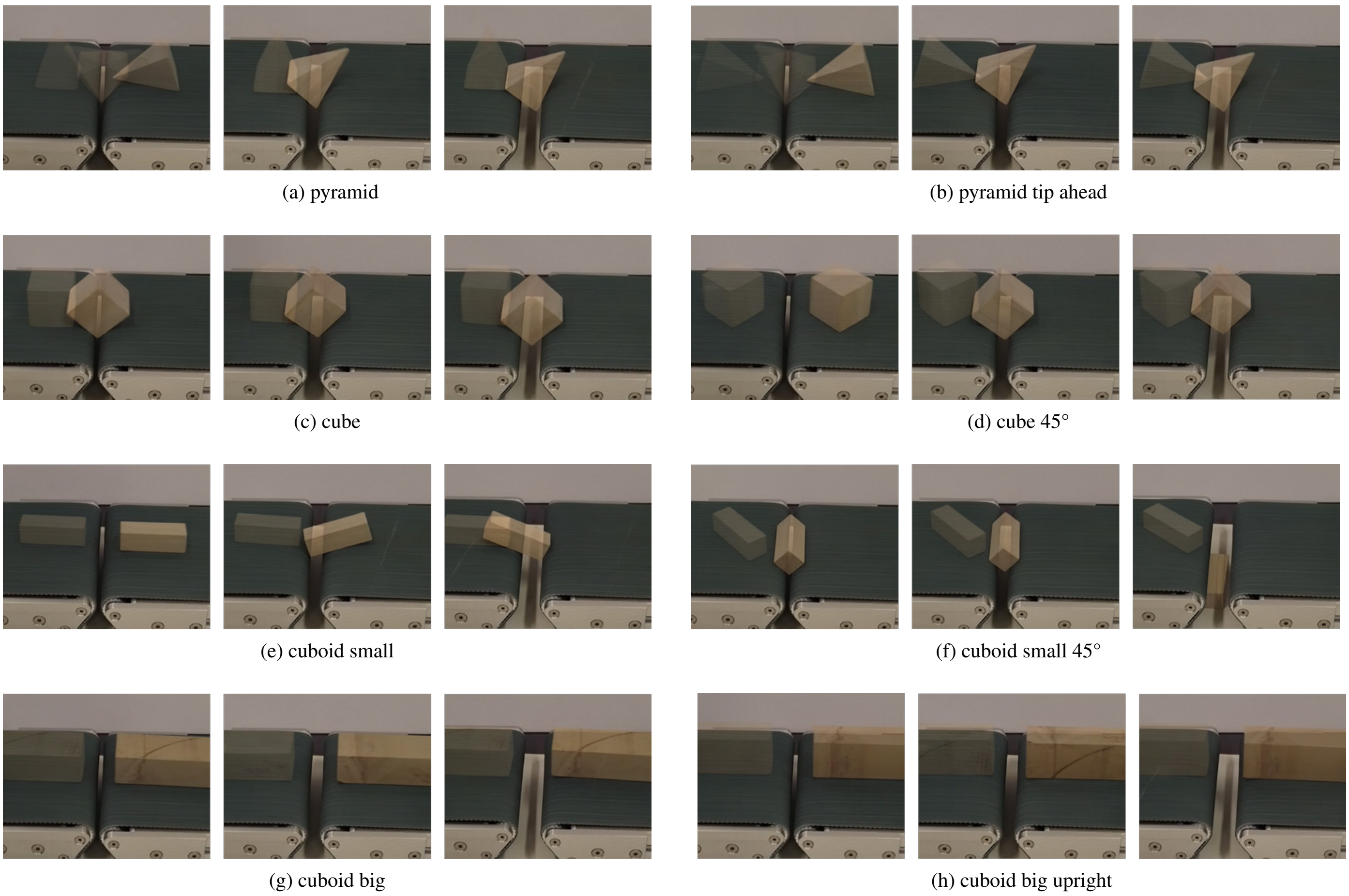
In the case of the material transfer system, the future goal is to enable the monitoring function to create an online decision support system. Before executing a material transfer, a virtual scene of the material transfer scenario is generated which essentially duplicates the current overall system state in the virtual world. Given the current information about the object to be transferred, highly parallel experiments can be conducted with the goal of predicting the probability of a successful transfer. The results can be returned to the production control to support in further decision making.

3. Analysis of the physics-based sim-to-real gap

Meaningful conclusions for real world decisions require an accurate virtual model. To be able to predict the feasibility of a material transfer given an object to be transferred, the physical interface between the TM and the TU is of particular importance. In the following we present the results of real-world experiments and improvement steps to reduce the sim-to-real gap of the virtual models.

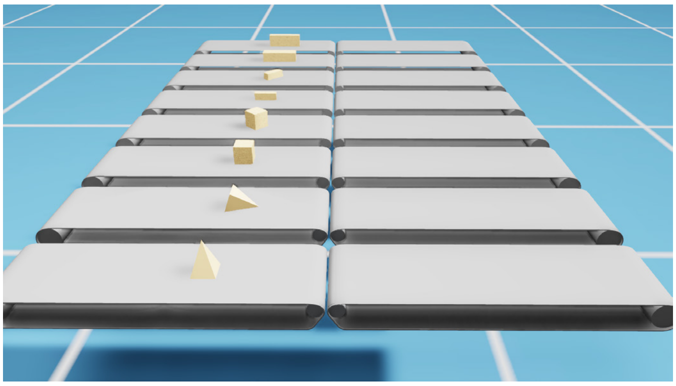
3.1. Real world experiments

Figure 5 and table 1 show the results of experiments to determine the object behavior during a material transfer. The experimental setup consists of two aligned conveyor belts, with three different gaps (7 mm, 15 mm, 25 mm). For this experiment, we transferred four different simple objects (pyramid, cube, small cuboid, big cuboid) in eight different configurations, resulting in 24 data points. All objects are made of wood, are rigid, and their masses are evenly distributed over their volumes. For the smallest gap (4 mm), only the cube and the small cuboid rotated by 45° cannot be transferred and get stuck in the gap between the two conveyors. The pyramid (both in the flat and tip ahead

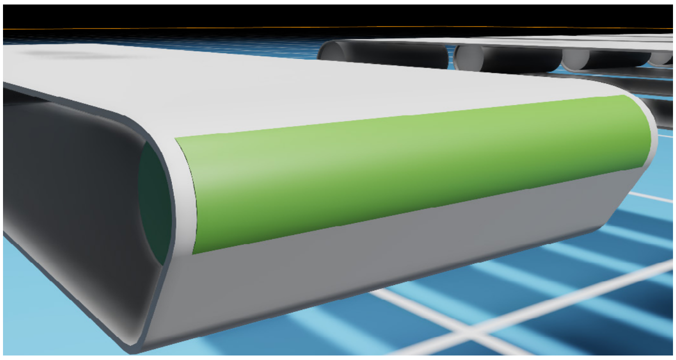


(a) pyramid (b) pyramid tip ahead (c) cube (d) cube 45° (e) cuboid small (f) cuboid small 45° (g) cuboid big (h) cuboid big upright

Fig. 5: Images taken during dynamic transfer experiments of simple shapes at a conveyor speed of 1 m/s and varying gap size between the conveyor belts (4 mm, 12 mm, 22 mm)



(a) Simulation scenario with eight parallel material transfer operations



(b) Collision model of the conveyor at the transition point

Fig. 6: Physics simulation in NVIDIA Isaac Sim of material transfers of the objects mentioned in table 1

configuration) shows a flip that changes the orientation. The cube rotates constantly in the gap, similar to the small cuboid rotated by 45°. For the second gap size (12 mm), the 45° rotated cube also rotates, while both pyramids no longer flip and do not transfer successfully. For the largest gap size (22 mm), the small cuboid cannot pass the gap, while in the 45° configuration it falls into the gap. The big cuboid can be transferred successfully for all gap sizes.

3.2. Modeling procedures in simulation

Figure 6a shows the simulation scenario in which all eight transfers are done in parallel. Firstly, the real objects were measured and weighted to parameterize their VMs. Since the masses of the test objects are evenly distributed, the center of mass position and inertia matrix can be calculated automatically. The modeling of the conveyor belt presents a challenge. Due to the motor load, the conveyor belts cannot be tensioned too much. The resulting curved surface differs significantly from the idealized mesh model that is usually supplied by the manufacturer. In addition, the circulating motion of the belt cannot be directly represented in a rigid-body simulation. Therefore, in order to simulate the crucial transition point of the conveyor belt, a combination of the mesh model with a rotating cylinder inside it was realized, see figure 6b.

3.3. Simulation results and discussion

Figure 7 shows the results of a set of simulation experiments for six different transfer scenarios. The scenarios match with the real world experiments, see figure 5a - 5f. During the experiments, both the gap distance (4 – 27 mm) as well as the static and dynamic friction coefficient (0.3 – 0.9) of the material pair were altered. For each object, one can observe different states and transfer outcomes depending on the parameter combination.

For the pyramid, both in upright and tip ahead configuration, we can observe a total number of five different states. For small gap distances, the pyramid can be transferred without any change in its relative pose. For increased distances, the pyramid either gets stuck or performs a flip, which could also been observed in the real world experiments, see figure 5a and 5b. In general, an increased friction coefficient leads to a shift towards more successful transfer states.

The small rotated cuboid can be successfully transferred for an increased gap distance compared to the real experiment (figure 5f). Similar results can be observed for the rotated cube (figure 5d). In the real experiment, the cuboid gets stuck in the gap already at the smallest gap distance. This suggests for another iteration on the mesh modeling as described in section 3.2. The currently used model only considers the unevenness of the belt in the longitudinal direction. However, the real conveyor belt also has an uneven surface in the transverse direction. We assume that especially the rotated and relatively small objects are affected by this unevenness which could explain the greater differences in the simulation results compared to the real experiments.

4. Conclusion and outlook

The uncertain condition of used products poses a major challenge for the automation of the disassembly process in remanufacturing. For the material transfer in such a system, we proposed a digital twin system architecture that models the physical and logical assets as encapsulated smart entities, that are capable of communicating on the cyber layer. Each physical

Table 1: Real world experiment results

Object	gap distance 7 mm	15 mm	25 mm
pyramid	2	4	4
pyramid tip ahead	2	4	4
cube	3	4	4
cube 45°	1	4	4
cuboid small	1	4	4
cuboid small 45°	4	4	4
cuboid big	1	1	1
cuboid big upright	1	1	1

[1] success [2] flip [3] rotates [4] stuck
[5] falls in gap

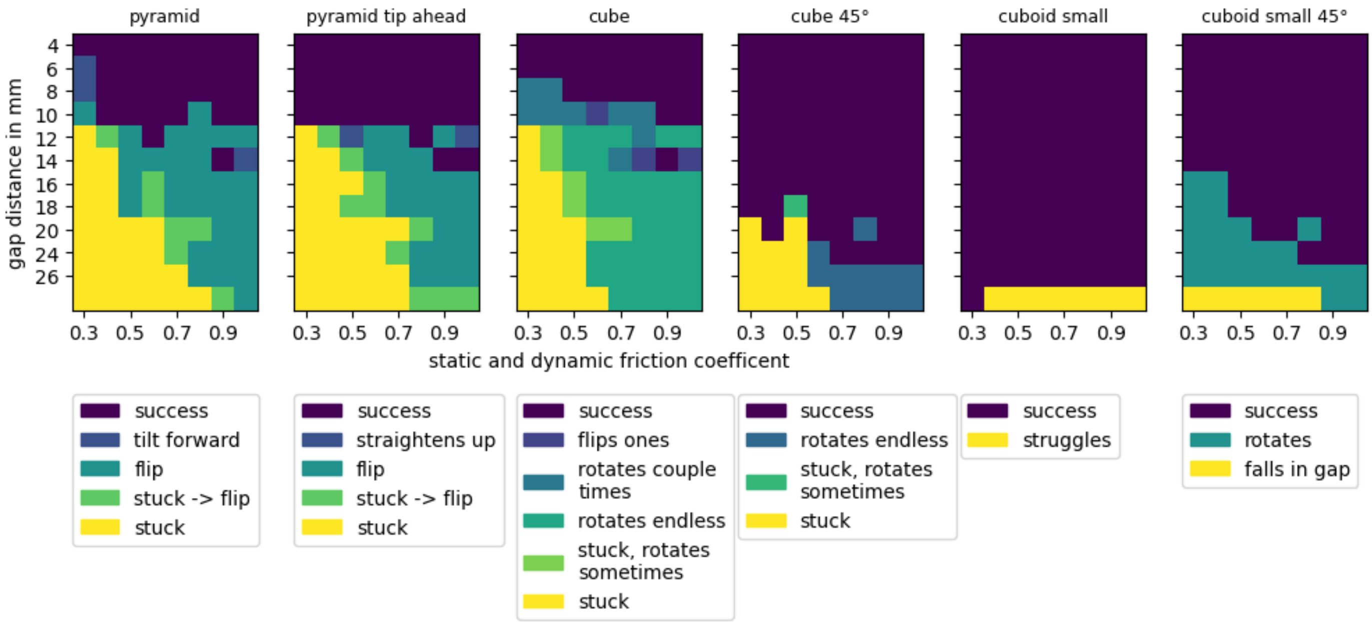


Fig. 7: Experimental simulation results for varying gap distance and friction coefficient

entity has its virtual model that can be simulated to continuously predict future states of the system or the success of a current operation. We additionally analyzed the sim-to-real gap for the material transfer of simple shaped objects between two conveyor belts. The comparison between real-world and simulated experiments suggests for accurate modeling and parameterization to ensure realistic physical behavior. Since the mesh modeling seems to be of particular importance we will further conduct more experiments with different mesh models of the conveyor belt. In the future, a complete pipeline for the decision support system will be implemented, which uses the proposed DT architecture to estimate the probability of success of the object transfer given an individual set of object characteristics. Besides the conveyor-based material transfer, another transfer scenario based on robotic picking will be evaluated and compared.

Acknowledgements

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