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Automatic simulation-based design and validation of robotic gripper fingers

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ABSTRACT

The design of robotic gripper fingers is a complex process and often requires significant effort and time. This paper investigates a method to automatically generate new iterations of the gripper finger design as well as to validate its performance in a simulation environment. A Computer-Aided Design (CAD) software platform and a physics-based simulation framework are deployed to work in tandem to redesign and validate an initial gripper finger design aiming at reducing the overall time and cost required for physical validation. The proposed approach is validated in a real robotic case scenario, performing a series of pick and place tasks.

1. Introduction

Novel developments in the area of Digital Manufacturing (DM) platforms have provided engineers with cost-effective and innovative solutions towards devising new design methodologies and approaches. DM platforms provide various levels of decision support and feedback to the engineer to improve the design of the product [1,2]. Modern Digital Engineering (DE) concepts may be realised during the process of new product prototyping [3]. A major challenge faced by design engineers in the field of robotics is the design and validation of robotic gripper fingers, which may be a tedious iterative process and can take up to several weeks even for an experienced designer [4]. Well-designed gripper fingers can improve the performance of a robotic cell significantly [5].

Recent studies have highlighted the need for more sustainable methods during the product design process. For example, the design and validation process of robotic gripper fingers can be improved with the help of technologies, such as Additive Manufacturing (AM), Computer-Aided Design (CAD), Topology Optimisation, and Generative Design approaches combined. Such approaches may reduce the wastage of raw materials and improve the production performance [6,7]. Furthermore, rapid prototyping methods involving parametric modelling, geometrical analysis, and grasp planning and analysis have shown promising results for designing robotic gripper fingers [4]. Although these design approaches may provide a satisfactory analytical base for evaluating the performance of a gripper design for specific parts and certain conditions, they still require an experimental validation to ensure robustness and fidelity, which can be achieved by carrying out a repeated number of physical experiments. Overall, in terms of testing, the validation of the design of robotic gripper fingers will typically require the use of a real robotic cell. This, in turn, necessitates the allocation of a number of resources to perform the experimental validation and may lead to the disruption of the manufacturing activities in the shop floor.

Modern DM approaches, including Virtual Commissioning (VC), are often employed to validate robotic configuration elements during the deployment phase [8]. While VC techniques are used in industry, there are some limitations when it comes to closing the gap between virtual and physical models. This gap calls for the physical validation of cell design decisions, by building and testing a physical prototype of the cell before finalising the design and completing the deployment phase. The use of simulation-based approaches may lead to the decrease of the disruptions occurring due to physical validations. In particular, physics-based simulation models and experiments may lead to the reduction of the time needed for validating production processes by testing different cell design and configuration elements within the simulation environment [9]. Physics-based models and tools may be used for simulating robotic tasks [10]. The use of physics engines in simulation aims to close the “reality gap”, i.e., minimise the differences between a real model and the digital model [11].

This paper proposes a novel approach, which aims at modifying the design parameters of robotic gripper fingers in an iterative manner considering the feedback from the tests carried out in a physics-based simulation environment, all of these in an automated way. For this purpose, in this paper a parametric design strategy is employed during the phase of determining the characteristics of the robotic gripper fingers. This approach allows the generation of different variants of the initial base design [12]. This is achieved by defining the key design parameters and varying them when required [13]. Each time a new design is generated, a series of simulation experiments are carried out to determine the performance of a specific design in a series of pick and place tasks.

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2. Methodology

One of the key challenges when it comes to validating cell configurations is that it is often required to test a configuration in a series of iterations, repeating a number of tasks, such as designing a specific piece of hardware (for instance gripper fingers), analysing its performance using simulation-based or analytical methods and then validating its performance employing physical experimental setups. This is typically a complex and time-consuming process leading to increased labour costs, lead times and production disruptions. In particular, this poses a direct challenge for system integrators while designing or reconfiguring a robotic cell. For example, the gripper fingers might have to be redesigned and tested when the workpiece to be handled changes in a new production scenario. To address these challenges, the proposed approach focuses on:

1. Automating the process of modifying an initial parametric model of the gripper finger design, which has been developed using CAD software.
2. Validating the parametrically modified design of the gripper fingers in a physics-based simulation environment. This is achieved by performing a number of pick and place tasks using an industrial robotic arm in a virtual environment. This strategy reduces the time spent on the physical validation of the design. Only the designs that show promising results will be prototyped and further tested in a physical environment.

2.1. *CAD software - Parametric design of the gripper finger*

A commercial CAD platform [14] was used to design an initial parametric model of the gripper finger, as shown in Fig. 1, step 1. The Application Programming Interface (API) of the platform allows external scripts to create or modify the design by controlling the parameters set by the designer. In particular, these parameters may be accessed and modified by an external parameters control algorithm. The CAD software can calculate physical properties, such as the weight of the object based on the material type that can be defined in the simulation environment.

2.2. *Simulation and validation in a physics-based environment*

A digital model of the industrial robot was developed in the simulation framework, comprising CoppeliaSim and the Vortex physics engine [15,16]. The educational licence version of the CoppeliaSim was used in this work. Then the gripper devoid of fingers was attached to the robot. Next, a 3D model of the gripper finger is imported into the simulation environment. Two identical gripper fingers are automatically mounted onto the end-effector of the industrial robotic arm in the simulation using a local script. The physical properties of the fingers, such as the weight, are updated within the physics engine in the simulation environment, and can be specified by the user directly or can be obtained from the CAD platform. Objects with different geometries, such as the ones shown in Fig. 2, may be imported manually into the simulation environment for testing. Each unsuccessful pick and place operation initiates the automated redesign process, and a new design is automatically imported into the simulation model for further testing. For instance, in case the pick and place task fails, the simulation is stopped and the next design variant is generated and tested, which allows for the faster convergence to a solution. The search process progresses iteratively by varying the design parameters of the gripper finger in small increments. It is expected that the proposed iterative approach will perform sufficiently well for a large number of realistic test cases and scenarios.

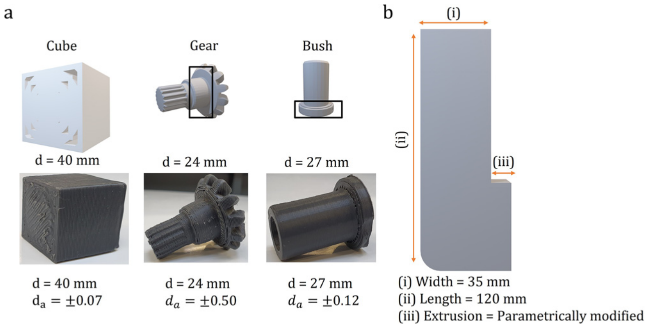

Fig. 2. (a). Workpiece designs tested using the proposed approach (b). Gripper parameter modified for experiments.

2.3. *Parameters control algorithm*

A parameters control algorithm was designed and implemented as part of the proposed approach, acting as the interface between the CAD system and the process simulation platform. It serves as the point where the feedback from the simulation software after the simulation experiments are executed, such as the task success or failure rate, is utilised to take actions, such as to parametrically update the CAD design of the gripper finger.

This algorithm initialises a set of parameters and constraints for the CAD and simulation platforms to be used while testing the gripper finger design. These include the number of times the gripper

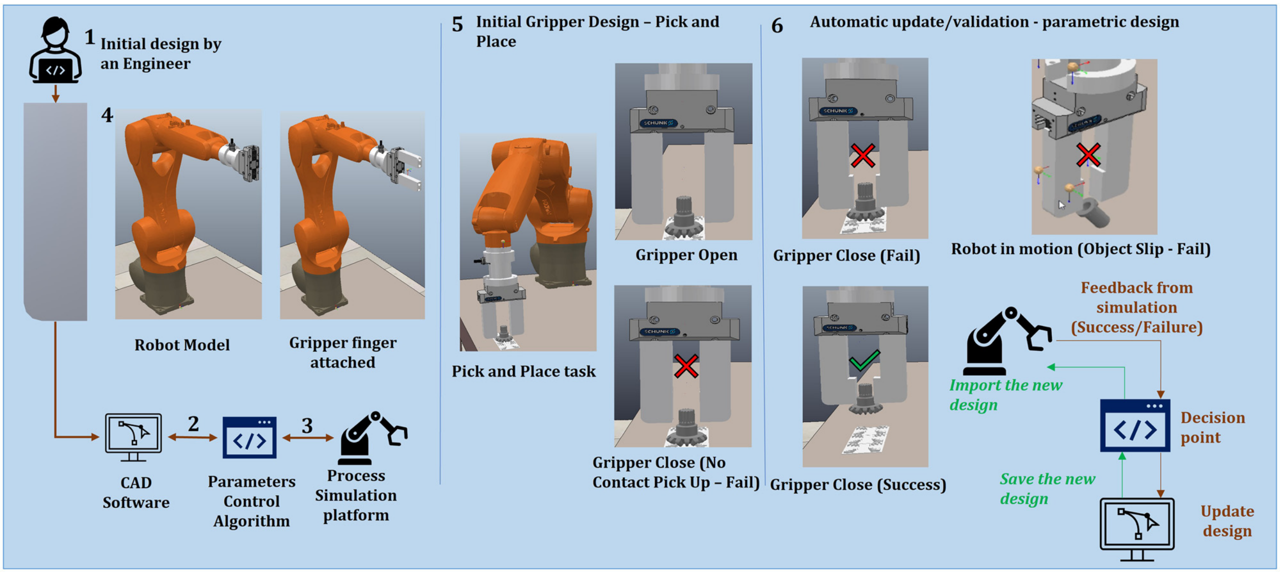

Fig. 1. Simulation-based design and validation of gripper finger.

design should be tested against the specific task, the maximum number of iterations, the minimum success rate under which a new design will be generated, the gripping force, the co-efficient of friction for the workpiece and a series of dimensional constraints, such as the maximum permissible length and width of the end-effector. The overall process involves the following steps (Fig. 1):

1. The designer creates the initial 3D model of the gripper finger using the parametric design approach and the CAD platform, then exports and stores the model as an Object (OBJ) file.
2. The parameters control algorithm retrieves the gripper design and performs a parametric update of the CAD model after the first iteration.
3. The workpiece is imported into the simulation environment and its pose is determined as per the process requirements.
4. The gripper fingers are mounted to the end-effector of the robot in the simulation model. This process is carried out automatically with the help of the simulation platform's API.
5. The test sequence starts with the robot attempting to pick and place the workpiece. A virtual force sensor attached to the gripper fingers in the simulation model is used to verify if the workpiece has been picked up successfully or not.
6. Based on the simulation result, a new design iteration is initiated where the design parameters are modified with the increment step being equal to ±0.05 mm.

The sequence runs until a design variant is obtained that is capable of successfully picking and placing the workpiece with the minimum success rate or the maximum number of design iterations is reached. The dimensional increment, the maximum number of iterations as well as the number of simulation experiments and the minimum success rate are user-defined parameters.

3. Experiments and results

In order to validate the proposed approach, a realistic case scenario was devised and tested. For this scenario, the extrusion parameter (parameter iii in Fig. 2) has been selected as the one to be varied over a series of iterations in a robot pick and place process. The case scenario includes a six-axis degrees of freedom industrial robot and a two-finger parallel gripper. The digital model of the overall process together with the real robot configuration are shown in Fig. 3. The simulation platform executes 50 pick and place experiments for each design variant. In each design iteration the task success rate is recorded by the simulation platform. The minimum success rate was selected to be 80%. In the case this success rate is achieved, the overall process is terminated, and the final design is 3D-printed and tested with the real robot. The same number of experiments were performed using a real industrial robot to validate the selected finger design variant, as it has been identified by the proposed search approach.

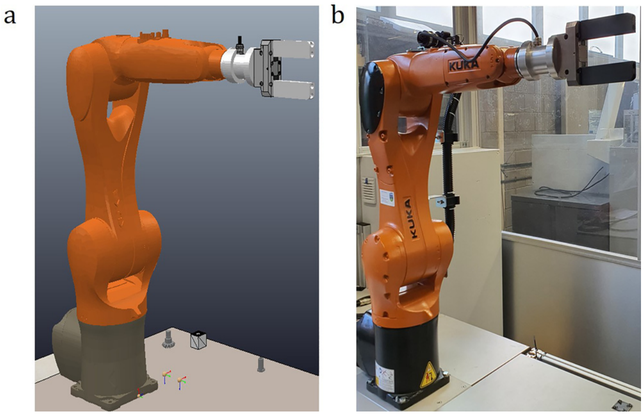

Fig. 3. (a) Digital model – simulation (b) Real robot.

The simulation time step was set at 50 ms, and Vortex was selected as the physics engine with a simulation pass per frame (ppf) set at 1. Also, robot parameters such as velocity, acceleration, and gripper jaw speed were configured to reflect the real operating parameters [17]. The gripper model in the simulation uses a force sensor to verify the success of picking and placing the workpiece. The force setting in the actual robot was set to a minimum by decreasing the current, setting the gripping force to 170 N. The gripping process in the simulation model and the real process with the actual gripper are shown in Fig. 4. The figure shows the closed position of the gripper after the object has been picked up.

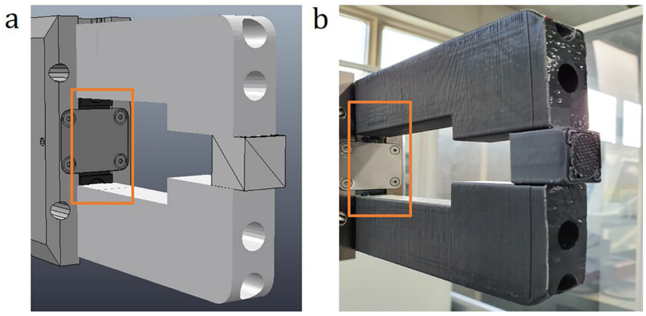

Fig. 4. Closed position of the gripper after the object has been picked up: (a) Simulation (b) Experiment.

A number of design iterations were carried out and tested with the simulation environment to generate a gripper design that was capable of picking and placing each of the individual workpieces. The shape and geometry of these workpieces are shown in Fig. 2(a), along with the grasping region of the object marked in black. The design of the gear and the bush shown in Fig. 2(a) were obtained from an exiting dataset [18]. The point of grasp was similar in both simulation and experiment. The same initial design of the gripper was used for all the workpieces in the first iteration. The initial design can pick up objects with dimensions within the range of 30.06 mm to 50.06 mm. When the dimension of the workpieces is less than 30.06 mm, the proposed approach will still generate parametrically modified gripper designs that can achieve the success threshold of 80%. Table 1 shows the experimental results. Each of the workpieces and the new finger designs selected using the simulation were 3D-printed using Acrylonitrile Butadiene Styrene (ABS). The printed fingers were mounted onto a real robot for validating the results obtained in the simulation.

Table 1
Simulation and experimental results.

Object Name	Dimension (mm)	Extrusion length (mm)	Simulation Result	Experimental Validation
Cube 1	40	$E_{c1} = 0.01$*	Success	Success
Gear Test 1	24	$E_{G1} = 4.51$	Fail	Fail
Gear Test 2	24	$E_{G2} = 5.01$	Fail	Success
Gear Test 3	24	$E_{G3} = 6.01$	Success	Success
Bush Test 1	27	$E_{B1} = 2.01$	Fail	Fail
Bush Test 2	27	$E_{B2} = 3.01$	Success	Success

* Initial Gripper Design.

The physical experiments proved that there is a close correlation in terms of the success rate between simulation and real experiments However, the quality of the 3D printed part may have a considerable effect on the real-world process. For instance, the grasping region of the bush workpiece at the bottom (27 mm, as shown in Fig. 2) is smaller by 3 mm than the minimum gripping distance when the initial gripper design is considered. The result of the proposed approach shows that the length of the parametric extrusion for a successful pick in the simulation was 3.01 mm. Experimental validation was carried out with a 3D printed gripper finger using ABS (Table 1). In the case of the Gear Test 2, the outer diameter of the 3D printed gear, corresponding to the grasping region, was approximately 24 mm with a maximum deviation of 0.50 mm. The selected dimension of the gripper finger was $E_{G2} = 5.01$ mm and the printed finger had a maximum deviation of 0.10 mm regarding this dimension and a warping closer to the mounting. These dimensional discrepancies of the workpiece and the gripper finger led to a successful grasp during the real-world experiment, while the process failed during the simulation. This is one of the limitations when testing the proposed approach using 3D-printed parts. This limitation can be overcome by using metal parts produced with CNC machining.

4. Conclusions and future work

Modelling the shape and texture of complex workpieces as well as considering the deformation of the gripper fingers during the grasping process may be challenging when using certain physics engines in a simulation environment. Most physics engines employ shape approximation techniques in order to reduce the overall required computational requirements. This affects the fidelity of the simulation process and sets a series of limits in terms of fully imitating the real process. In other words, bridging the “reality gap” is still an issue that needs further attention.

One of the main advantages of the approach presented in this paper is that it can be utilised for testing a number of different configurations of the gripper design for handling multiple workpieces provided there is enough computation power to run the simulation. The proposed approach may be used to iteratively vary other parameters of the gripper finger, such as the material as well as other geometrical features, including the overall dimensions respecting the gripper requirements or constraints. By taking advantage of other Computer Aided Platforms’ (CAx) APIs, Finite Element Analysis (FEA) features may be integrated in the physics-enabled simulation-based design validation under one package, as shown in Fig. 5.

The ultimate goal of the proposed approach is to demonstrate the advantages of physics-based simulation towards automating the process of design and validation of robotic cell configurations. Conventional approaches involve the validation of configurations by performing time-consuming and production disrupting physical experiments. The proposed approach may lead to drastic reductions of the number of design iterations and associated costs. The current physics engines limitations are expected to be overcome over the next few years, allowing therefore for the consideration of far more complex workpieces and gripper finger geometries.

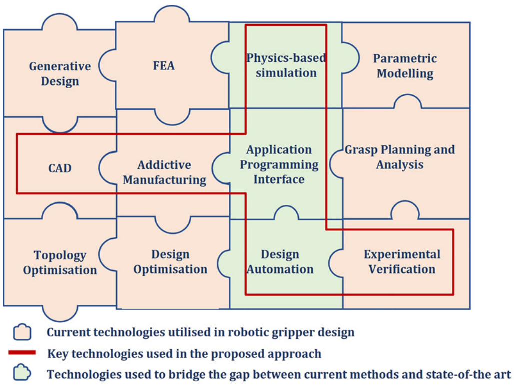

Fig. 5. Combination of various technologies utilised in the proposed approach and scope for integrating additional technologies in the future.

The very promising results of the proposed approach prove that a combination of CAD platforms and physics-enabled simulation frameworks can further automate the process of designing and validating specific elements of robotic process configurations, such as the ones related to gripper fingers. This approach can be further developed into a more reliable system by enabling the consideration of additional parameters, such as the moment of inertia, material properties, surface textures and coefficient of friction under different operating conditions in the simulation environment. In addition, other properties of gripper fingers, such as their wear during their lifetime may be considered during the simulation-based design process. Furthermore, the use of more sophisticated search and optimisation algorithms, incorporating Design of Experiments principles, will be considered in the future allowing for multi-dimensional search. Stochastic optimisation strategies for example could also address uncertainty related to the friction coefficient and part or finger tolerances.

Other elements of the robotic cell configuration, including sensors, fixtures and additional devices may be considered as part of a full Digital Twin (DT) process model that may lead to a more accurate representation of the overall robot-based process. For instance, integrating a virtual vision system in a simulation model may allow the consideration of the vision system accuracy during the gripper finger design process, while allowing some degree of uncertainty regarding the workpieces geometry.

In the future, it is expected that highly accurate and detailed process simulation models be fully integrated with CAx platforms for designing and validating robotic grasping processes in digital environments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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