Modeling of vacuum grippers for the design of energy efficient vacuum-based handling processes

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Abstract

Vacuum-based handling is widely used in industrial production systems, particularly for hand-ling of sheet metal parts. The process design for such handling tasks is mostly based on approximate calculations and best-practice experience. Due to the lack of detailed knowledge about the parameters that significantly influence the seal and force transmission behavior of vacuum grippers, these uncertainties are encountered by oversizing the gripping system by a defined safety margin. A model-based approach offers the potential to overcome this limitation and to dimension the gripping system based on a more exact prediction of the expected maximum loads and the resulting gripper deformation. In this work, we introduce an experiment-based modeling method that considers the dynamic deformation behavior of vacuum grippers in interaction with the specific gripper-object combination. In addition, we demonstrate that for these specific gripper-object combinations the gripper deformation is reversible up to a certain limit. This motivates to deliberately allow for a gripper deformation within this stability range. Finally, we demonstrate the validity of the proposed modeling method and give an outlook on how this method can be implemented for robot trajectory optimization and, based on that, enable an increase of the energy efficiency of vacuum-based handling of up to 85%.

Keywords Vacuum-based handling · Energy efficiency · Prediction model

1 Introduction

Automated handling of parts, which adds up to about 50 % of all robot-guided processes in production environments [1] and usually even exceeds the time used for actual machining [2], is often realized by means of vacuum-based handling techniques [3], in particular in the automotive field and for packaging tasks [2, 4]. For industrial high-volume handling applications, vacuum is typically generated pneumatically through ejectors, due to their fast and wear-free operation and the direct integrability into gripper systems. Hence, ejector-based hand-ling processes are in focus of this work. With regard to typical efficiency ratios of air compression and pneumatic vacuum generation, a maximum of 2% of

the initially invested electrical energy is eventually usable for the vacuum-based handling process (Fig. 1, top). In air compression, less than 10 % of the inserted energy can be used for vacuum generation [5], as the vast energy share is transformed to thermal energy by heat dissipation, which is reusable through heat recovery [6]. For vacuum ejectors, exergetic conversion efficiencies of up to 20% are calculated in [7].

However, as major research on energy efficient compressed air generation and distribution [8–15] as well as on the optimisation of ejector performance and efficiency was shown [7, 16–18], there is currently a lack of generally applicable methods for the design of vacuum-based handling processes. The process design for vacuum-based handling tasks is usually based on prior experience and best practice knowledge. Uncertainties such as leakage or the unknown force transmission behavior of vacuum grippers make it necessary to roughly estimate the process-specific loads and therefore oversize the system by a defined safety margin. Subsequently, by use of the existent handling system, experimental trial-and-error tests are carried out for identification of advantageous operating parameters. Therefore, in order to

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Fig. 1 A small process-related decrease in energy consumption has a huge impact on the overall energy consumption of the entire handling process

eliminate the necessity of such extensive efforts to achieve a highly energy efficient vacuum-based handling process, the objective of this work is to provide a vacuum gripper model that can be applied for design optimization of a vacuum-based handling system and process.

With such a model, the gripper deformation that occurs during the process due to the applied mass and its acceleration through the implemented robot motion can be predicted. The robot trajectory can then be optimized in such a way that the loads at the gripper-object-interface (GOI) do not lead to a critical gripper deformation which would eventually result in a permanently reduced suction force. Conservative methods are based on avoiding any vacuum gripper deformation to ensure a robust handling process. However, this paper raises the research hypothesis that it is possible to reduce the overall energy consumption by deliberately allowing for a certain limited gripper deformation. By downsizing of grippers and ejector as well as load-adapted trajectory planning, the energy consumption for vacuum generation can be significantly reduced. Therefore, a model is required that allows for the prediction of the gripper behavior due to the occurring loads at the GOI and thus enables the task-specific optimization of the robot trajectory.

Section 2 gives an overview on existing modeling approaches for vacuum grippers. These approaches are evaluated with regard to their applicability for model-based trajectory planning and gripper deformation prediction. In Sect. 3, we present an experiment-based modeling method for vacuum grippers and the experimental setup for obtaining the required data from selected industrial vacuum grippers. On the basis of this method, we introduce an extension of the standard model for estimation of the maximum bearable loads for specific suction grippers. For a more detailed

prediction of the gripper deformation due to process-induced loads, we introduce a dynamic surrogate model. In Sect. 4, the energy savings achievable through the presented modeling approach are elaborated. Finally, Sect. 5 ends with a conclusion of the presented work and gives an outlook for future work.

2 Related work

Various researchers present work on determining the achievable suction force of active vacuum grippers. The suction force is determined either by the active area resulting from deformation of the sealing lip or by the volume within the suction cup [19–24]. For simplification, in these publications the force applied on the object and the suction cup is regarded as point load. In general, the seal between gripper and object is not determined explicitly, but an ideal seal is assumed. However, based on such simplified model approaches that do not include object-specific seal properties, the specific force transmission and seal at the GOI cannot be determined to a sufficient level of detail.

In [25], the mass distribution of the object and the main form of the vacuum gripper are considered in more detail. Furthermore, Braun introduces an explicit sealing force that must be present in order to provide the required suction effect. Based on a static system analysis, the required suction force for a specific handling task is determined. Braun shows that pneumatic large-area suction grippers can be dimensioned adequately by the use of static characteristic maps that describe maximum holding forces depending on gripper design and material. Bahr et al. extend this static system analysis by considering moments that occur at the center of the suction cup in order to determine the required pressure difference [26]. On this basis, Mantriota focuses on the minimum value of the necessary static friction coefficient [27–29]. Such generalizing models enable a quick estimation of the reachable suction force but do not provide deeper insights into the object-specific seal and the dynamic force transmission.

Initial work on dynamic models for vacuum grippers can be found in [30]. Radtke predicts the deformation behaviour of the suction gripper by means of a dynamic surrogate model that includes tilting, torsion, traction and thrust. The viscoelastic behavior of the flexible part of the gripper is modeled by means of a spring-damper element with the objective to determine the natural oscillation behavior of vacuum grippers and, on this basis, to develop grippers with improved damping behavior. Radtke gives concrete recommendations on adapted gripper designs based on experimental studies. Karako et al. propose a similar spring-damper model approach with the aim of improved acceleration parameters for the robot motion pattern. They showed

that the process cycle time can be tuned successfully based on the proposed model, but encountered significant accuracy deviations regarding the prediction of grasp stability [31]. Both Radtke and Karako model the spring-damper element with linear characteristics which enables a more detailed consideration of the dynamics applied to the grasped object. However, the feasibility of these approaches is demonstrated, but it is not transferred to industrial implementation in order to achieve technical improvements or energy savings.

Based on Braun and Radtke, Becker proposes an extended force model to identify the maximum force absorption of suction grippers for a variable surface roughness and object shapes [32]. Becker's model covers all motion directions of the manipulator and takes the relevant static and dynamic influences into account. Based on experiments, he provides general qualitative information about the examined interdependencies between certain design properties of gripper and object such as gripper design and material as well as object surface roughness and curvature. However, since only the maximum reachable force is determined for different gripper-object combinations, the detailed dynamic deformation behavior is not included. As the authors demonstrate in [30, 31], it is of great interest to gain knowledge about the exact deformation behavior of vacuum grippers due to a certain load state. Hence, in order to determine the maximum applicable suction force [33, 34], conduct finite element (FE) simulations. The setup of such an FE analysis requires many iterations because of the present nonlinearities of the rubber-like gripper material. In addition, it is crucial to carefully set up the boundary conditions to achieve a stable computation of the FE simulations. In [33, 34] the authors demonstrate good results with regard to an accurate prediction of the gripper deformation compared to real experiments. However, such effort-intensive simulation methods are not feasible for a quick model-based process and system planning.

The aforementioned research regards models for single vacuum grippers, but also several publications can be found that aim at the transfer of such knowledge to the system level. In [25, 27–29, 35], the authors show strategies for the task-specific design of gripper systems that consist of multiple vacuum grippers. In detail, the maximum bearable forces and moments are calculated. Further, in [36, 37] methods are proposed for determining the optimal positions of multiple vacuum grippers on the object to be handled.

In summary, a substantial body of research proposes different modeling approaches to mathematically describe the behavior of vacuum grippers due to induced loads. The majority of the proposed methods are based on a static calculation method; few publications demonstrate feasible dynamic prediction models that can be implemented for model-based robot trajectory and also vacuum gripper design. The analyzed research suggests that the implementation of such a dynamic

prediction model in combination with the consideration of different object geometries and roughness offer great potential for model-based system and process design with the objective of improved energy efficiency. Therefore, the gripper deformation behavior could be predicted not only depending on the gripper design, but also under consideration of the influence of the gripper-object combination on the sealing and force transmission.

3 Modeling method for vacuum grippers

Numerous design- and process-related parameters influence the resulting holding force that can be generated by a specific vacuum gripper. At first, the most significant influence factors are extracted in order to specify the model structure and the strategy for experiment-based data acquisition. On that basis, both the extended standard model and the analytical surrogate model are specified with concrete measurement data from experiments.

3.1 Influencing parameters and model structure

The effective holding force results from multiple interdependencies of design parameters (for gripper and object) and process parameters (Fig. 2). It defines the force with that the vacuum gripper can encounter the weight and inertial force of an attached object. For example, a good form fit at the GOI reduces the leakage flow which would reduce the pressure difference available for generation of the holding force. The form fit is mainly influenced by the specific gripper-object combination, but will potentially be affected by process-induced loads at the GOI. A straightforward approach for determining the quantitative relations between these influencing parameters is to explore the resulting parameter space experimentally.

The required hardware and automation setup is time- and cost-intensive but makes up for high modeling and computational effort and—considering non-linear material behavior of the applied materials such as silicone or rubber—potential inaccuracies in simulations based on numerical models. The most simple possible approach is to measure the pull-off force of specific grippers and therefore enable a relative reduction of the oversizing margin. In this work, we firstly propose a model approach that extends the standard model by the influence of different gripper-object combinations on the pull-off force that is applied axially to the gripper. The standard model [38] calculates the maximum force F acting on the object by one vacuum gripper as given in Eq. (1):

$$F = \Delta p \times A \times z \times \frac{1}{S} \times n \times \eta \quad (1)$$

with the pressure difference Δp , the effective suction area A and the number of grippers z . By division by the safety

Fig. 2 The effective holding force is composed of both fixed design parameters and variable process control parameters

margin S , the theoretical holding force is reduced. The sealing and deformation behaviors of the gripper are expressed by the deformation coefficient n and the leakage factor η . Then, our **extended standard model** approach replaces the product of $n \cdot \eta$ by considering the influence of the object geometry, the gripper material and design in a single factor n_{GOI} . At a relatively low modeling resp. experimental effort, this approach offers the potential to reduce the need for oversizing since more detailed knowledge about the expected maximum force is available. Equation (2) shows the extension of Equation (1) by the proposed factor n_{GOI} :

$$F = \Delta p \times A \cdot z \times \frac{1}{S} \times n_{GOI}. \quad (2)$$

However, an analytic surrogate model is an adequate compromise between modeling effort and the remaining need for oversizing and allows to be built-up and refined through both experimentally acquired measured data and simulation

results. Thus, for a more detailed and accurate prediction of the gripper behavior, we propose an analytical **spring-damper surrogate model** based on a generalized Kelvin–Voigt model (parallel connection of spring and damper) as introduced in [30, 31]. In extension of the already pre-sent work, this model approach describes the gripper deformation due to axial and radial stress (in the scope of this work, we focus on the axial gripper behavior) as well as it considers the influence of the specific gripper-object combination and its influence on sealing and force transmission. The knowledge about process-induced gripper deformations and the corresponding grasp stability potentially enables to design robot trajectories and gripper systems in such a way that it can be assured that gripper-specific critical load values are never exceeded, while eliminating the need for oversizing.

3.2 Experimental setup for robot-based vacuum gripper characterization

A robot-based experimental setup has been built-up for acquisition of the required measurement data and is described in the following. Several grippers that are commonly used for metal sheet or package handling were selected for experimental characterization. For the objects to be grasped, there is no standardized definition of adequate geometries for such a fundamental characterization problem. Therefore, primitive test objects were designed parametrically to generate multiple geometry variants (Fig. 3).

In a robot-based setup (Fig. 4), the selected grippers ($\varnothing$ 60 mm) can be tested in combination with the different objects and—for further experiments in the future—at arbitrarily complex load cases. The experimental setup comprises of an industrial robot (KUKA KR60-3) with compressed air supply and a vacuum ejector with a pre-connected proportional valve to vary the ejector input pressure. For measurement of the occurring loads, a 6-D force-torque-sensor is used to which single vacuum grippers of different types can be attached. The force data are acquired at a sampling rate of 500 Hz. For vacuum generation, a compact ejector with integrated pressure measurement is used. The input pressure is varied by a proportional valve.

In this setup, the balance of forces between robot and the fixed test object provides direct information about the reaction forces inside the vacuum gripper, since the gripping area is fixed to the test object and the pulling force that is generated by the robot can be measured. Therefore, the measured force data can be directly used for model parametrization.

3.3 Extended standard model

For the extended standard model, the maximum achievable forces just before the gripper pull-off are regarded. In this

Fig. 3 Top: Parametric test objects (r_c : curvature radius), bottom: exemplary gripper-object combination

Fig. 4 Experimental setup for robot-based tests

work, grippers (provided by J. Schmalz GmbH) with 1.5 foldings of different gripper materials (nitrile butadiene rubber NBR, high temperature material HT, Vulkollan VU) are considered in combination with the object geometries. As these grippers were designed for different application fields, they differ in the detailed design of support structures and inner diameters. Table 1 shows the parameters that were tested in full-factorial experiments. 30 repetitions were conducted per parameter setting to compensate for statistical variance and outliers. The test runs were packed into batches of five runs per setting and then randomized in such a way that gripper and object were changed every five test runs.

The objective is to aggregate such influences into the above introduced factor n_{GOI} for a more precise prediction of the gripper-object-specific pull-off force. Therefore, pull-off tests were conducted with all selected test objects (and a plane object as reference) at a target velocity of 10 mm/s

Table 1 Test plan “extended standard model”

Parameter	Levels
Gripper material	NBR (60)
(Shore hardness in °Sh)	HT1/2 (60/65)
	VU (72)
Curvature radius r_c (mm)	Convex: 48, 66, 125
	Concave: 44, 59, 111

Fig. 5 The object geometry influences the achievable holding force significantly

(in orientation to the test velocity for tensile testing of rubber [39]). The test objects consist of milled aluminium and have an average surface roughness $R_z = 0.43 \pm 0.08 \mu\text{m}$ (six measurements in milling direction with Hommel Wave W10 skidded roughness gage). The input pressure for the ejector has been set to 4.0 bar for all tests since this is the most efficient operating point. On the basis of the force data and the gripper specifications provided by the manufacturer, the introduced factor n_{GOI} was computed for all gripper-object combinations as shown in Fig. 5. The third convex dome object could not be considered since the large curvature resulted in too strong leakage.

The gripper made of NBR does not reach the theoretically calculated holding force, since n_{GOI} is below 1 in all cases. The gripper made of HT2 material shows significantly lower forces than theoretically calculated, except for two concave dome objects. For the gripper made of HT1 material, n_{GOI} reaches the theoretical force in most cases. The gripper made of VU, however, provides exceptionally high suction forces, especially in combination with the concave dome objects. For a concrete mathematical description of the observed phenomena, a function $n_{GOI}(r_c, f_s)$ can be built via regression, where r_c is the curvature radius and f_s describes the degree of object symmetry. Such object-specific knowledge about the achievable pull-off force can potentially be applied to grasp planning problems where the optimal positions of the vacuum gripper on an object are determined. However,

it is further intended to elaborate a dynamic surrogate model to provide for a more detailed model-based process design.

3.4 Analytical spring-damper model approach

The objective of this spring-damper model is the prediction of the gripper elongation due to process-induced forces. With one selected gripper (SAB HT2), pull-off tests were conducted at 15 target velocities (0.5, 1, 5, 10, 25, 50, 75, 100, 125, 150, 175, 200, 225, 250 mm/s) at 3.0 bar in combination with only the flat object to demonstrate the modeling workflow. Here, a lower pressure level was chosen in order to achieve a relatively large gripper deformation for the model validation. 30 repetitions per parameter set were packed into six batches of five runs per target velocity setting and then randomized. Algorithm 1 shows the schematic procedure of the pull-off tests.

Algorithm 1: Dynamic pull-off tests

```

for  $i \leftarrow 0$  to  $\text{len}(\text{listOfVelocities}) * 6$  do
  for  $j \leftarrow 0$  to 5 do
    Attach gripper at  $POS_a$ 
    Vacuum on
    Wait 0.5 s
    LIN to  $POS_{\text{end}}$  with  $v = \text{listOfVelocities}[i]$ 
    Vacuum off
  end
end
end

```

As a first step, the spring characteristics were extracted from the pull-off test at 0.5 mm/s, which can be regarded as quasi-static. The regression can be conducted with the following kernel function:

$$F_{\text{spring}}(x) = ab + x^{-b \times (x-c)}, \quad (3)$$

Figure 6 shows the regression (mean squared error, MSE, over all curves of 0.897 N^2) of the quasi-static pull-off measurement for the selected vacuum gripper.

Regression of all force measurements provides a 3D-map of the resilience inside the vacuum gripper (dashed in Fig. 7). In accordance with the equilibrium of forces that is present inside the spring-damper element during the pull-off experiments, the difference of the force curves and the quasi-static spring characteristics curve results in the damping characteristics (dotted in Fig. 7).

The elongation velocity is displayed only up to 160 mm/s because higher target velocities could not be reached by the robot due to acceleration limits. Using a fourth degree polynomial as kernel function, a regression of the damping force $F_d(\dot{z})$ dependent on the elongation velocity $\dot{z}$ can be calculated (MSE=7.001 N^2). By fitting of the curve-wise polynomial coefficients, a two-dimensional regression of the

Fig. 6 Non-linear regression of the spring characteristics

Fig. 7 Multidimensional non-linear regression of the damper characteristics from the measurement data

damping force dependent on the actual elongation z and the elongation velocity $\dot{z}$ provides the damping force as shown in Eq. (4).

$$F_d(z, \dot{z}) = a(z) + b(z) \times \dot{z} + c(z) \times \dot{z}^2. \quad (4)$$

Hence, the damping force can directly be calculated for a specific combination of z and $\dot{z}$ (green in Fig. 7). For the numerical computation of the gripper elongation due to externally applied forces, the resulting damping factor can directly be extracted.

In the first section of this paper, we raised the **research hypothesis** that it is possible to reduce the overall energy

consumption by deliberately allowing for a certain limited gripper deformation. This would require that the gripper deformation is fully reversible below this limit. In order to evaluate this assumption, further pull-off tests are conducted at a velocity of 10 mm/s (this velocity was chosen for a relatively low time required for conducting the experiments; the velocity dependency of the deformation will be examined in the future). After full attachment at POS_a the elongation is firstly generated until the target position POS_t is reached, reset to POS_a and pulled off entirely to ensure independent data. This is repeated 30 times. The z -component of POS_t is increased stepwise by 1 mm until the maximum elongation is reached.

Algorithm 2: Reversibility pull-off tests

```

for  $i \leftarrow 0$  to  $maxElongation$  do
  for  $j \leftarrow 0$  to 30 do
    Attach gripper at  $POS_a$ 
    Vacuum on
    LIN to  $POS_t$  with  $v=10$  mm/s
    LIN to  $POS_a$  with  $v=10$  mm/s
    Complete pull-off with  $v_{max}$ 
    Vacuum off
  end
   $POS_{targ}.Z += 1$  mm
end

```

Figure 8 shows the resilience force that is generated in the vacuum gripper (by applying an external pull force) and then decreased (due to the release motion back to the initial position POS_a). Up to a certain limit (around 13 mm), a slight hysteresis can be identified, but the resilience force in- and decreases steadily. Above that limit, the force drops significantly as soon as the release of the external force begins. The tests at all other target positions are displayed in light gray for better visibility of the highlighted curves.

With regard to a handling process in industrial practice, this implies that a gripper deformation up to the identified

Fig. 8 The gripper deformation is determinately reversible

limit can be described as reversible. Above that limit, the gripper is not able to retract immediately which indicates that a permanent deformation will remain.

3.5 Experimental validation of the spring-damper model

For experimental validation of the proposed spring-damper model, the robot end effector was equipped with an ultrasonic distance sensor (Balluff BUS0026) directed to the top face of the test object (flat surface, 2.4 kg). In order to enable a significantly visible gripper elongation, the input pressure was set to 3.0 bar for a reduced suction flow. Initially, the vacuum gripper was in full contact with the test object. Subsequently, the robot was accelerated in the z axis and stopped at a target position of $z_{max} = 680$ mm. Figure 9 depicts the measured and simulated gripper elongation.

The simulation of the elongation was conducted by numerical calculation of a generalized Kelvin–Voigt model where spring and damper are arranged in parallel. The inertial force of the attached mass was calculated by means of the acceleration that is applied due to the robot trajectory. The results of the simulation do not match the measured data. The simulated maximum elongation is however close to the measured values. The apparent prediction errors can potentially be attributed to phenomena of the gripper deformation behavior that cannot be modeled with the proposed spring-damper model. Moreover, a detailed model of the retraction behavior of the gripper may improve the simulation results. In this validation experiment, a simplified robot trajectory was used to evaluate the gripper elongation. Nevertheless, the model can be applied to determine critical deformations in the context of robot trajectory optimization, given that the prediction accuracy will be improved significantly. The proposed experiment-based modeling method is generally feasible and can also be applied to other gripper-object combinations for a prediction of the gripper

Fig. 9 Experimental validation of the non-linear spring-damper model

deformation that is more detailed than previously available methods.

4 Reference scenario: potential energy savings by model-based process design

An industrial reference scenario is introduced in the following to estimate the potential energy savings that can be achieved by application of the elaborated model approaches. For a fictitious pick and place task where a 1×1 m aluminium sheet is to be transferred between two defined positions within a cycle time of 4 s, J. Schmalz GmbH provided a gripping system including a vacuum ejector that were dimensioned conservatively by use of the standard calculation scheme as shown in Eq. (1). This gripping system comprises of four round bell suction cups (diameter 60 mm) that can be evacuated by an ejector with a suction flow rate of 36 l/min. At a recommended target pressure difference $\Delta p = 600$ mbar (and the programmed robot trajectory for completion of one handling cycle in 4 s), no gripper deformation occurs. Assuming that the resulting deformation will still remain within the specific stable range as examined in Fig. 8, it is possible to reduce the gripper size to a diameter of 50 mm (orange in Fig. 10). The gripper dead volume would be reduced by 41 % compared to the original grippers, which directly leads to a proportionally reduced consumption of compressed air that is required for evacuation of the dead volume (tubings neglected). Further, it is plausible that the ejector could also be downsized since it may take the same time for evacuating a reduced volume, and therefore a reduced suction flow rate could be sufficient. The result is a halved compressed air consumption. Downsizing both

the gripper and the ejector would result in a total energy use reduction to 29.5 % of the originally required energy input.

Own experiments have shown that an adapted control strategy for the built-in air saving function of the used compact ejector has a significant impact on the compressed air use as well (green in Fig. 10). An increase in the pressure hysteresis (the range within that the pressure difference is allowed to drop before the ejector starts to generate vacuum in order to maintain a stable level of vacuum) by 100 mbar enables a relative reduction in energy consumption of 10%. When we reduced the target pressure difference from 600 to 500 mbar, this resulted in 55% of the original air consumption. Again, a combination of both control strategies achieves more than 50% energy saving. A larger increase of the pressure hysteresis and decrease of the pressure difference lead to significant gripper deformations. At the specified control parameters $\Delta p = 600$ mbar and a hysteresis of 150 mbar, the grippers did not show any noticeable deformation. In general, it must be critically evaluated whether a combination of multiple separate downsizing strategies keeps the gripper deformation within the stable range, since minimal leakage between gripper and object is a prerequisite for application of the described energy saving strategies. However, combining all proposed strategies enables an overall reduction to less than 15 % of the original energy consumption.

5 Summary and outlook

In this work, an experiment-based modeling method for vacuum grippers was presented. The initially introduced extended standard model considers the specific influence of a certain gripper-object-combination on the resulting maximum holding force. This approach potentially allows for a relative downsizing of a vacuum-based gripping system in comparison to the standard model. Based on present research on dynamic surrogate models for vacuum grippers, we demonstrated that on the basis of more extensive testing, a detailed spring-damper-model can be built from test data. Experimental data are publicly available at <https://lnk.tu-bs.de/AmMnbw>. It was further shown that the dynamic gripper elongation can be predicted qualitatively by means of this surrogate model. However, the occurring prediction errors show that not all phenomena can be modeled sufficiently with the spring-damper approach and must be further investigated in order to enable a precise model-based robot trajectory optimization. With respect to the research hypothesis raised in this work, it can be summarized that the proposed modeling method does not only provide the basis for highly task-specific process and system design optimization, but can also reliably secure these design decisions with knowledge about the gripper deformation reversibility and

Fig. 10 Allowing a limited gripper elongation enables significant savings of the energy required for vacuum generation

thus significantly reduce the need for oversizing. Hence, the energy that is needed to realize vacuum-based handling tasks can generally be decreased to a large extent.

In future work, alternative respectively more complex model structures and further regression methods will be evaluated in order to increase the prediction accuracy. In addition, we will evaluate if it is possible to reduce the experimental effort in such a way that a valid model can still be achieved. For example, this could be achieved through generalized pre-trained neural networks that are then post-trained with data from the gripper-object-specific experiments. Up to now, the industrial practicability of the proposed modeling method is limited by the required amount of test data. Whereas subsequent regressions were applied to simplify the position- and velocity-dependent determination of spring- and dam-per parameters in the dynamic simulation, the resulting regression error could be reduced by a more complex representation of the spring- and dam-per characteristics. With regard to the influence of the gripper-object-combination, both proposed model approaches will be extended by considering tests with different object surface roughness. This augments the solution space for the optimization of the robot trajectory or the determination of the optimal gripper positions on a specific object.

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