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Energy-efficient handling through passive vacuum generation and biomimetic functional principles

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Abstract.

Automated handling is an established process within the context of industrial and automated production, usually carried out by robotic systems with gripper systems. Conventional suction grippers rely on compressed-air-based vacuum generation – with a significant associated energy consumption and required infrastructure. A possible alternative is the usage of passive vacuum-based handling technologies, which offer the opportunity to entirely avoid the previously necessary expensive infrastructure. However, within the current state of development, passive systems inherently lack pressure regulation capabilities, which introduces the risk of vacuum leakage and therefore a reduced gripping reliability. The present research therefore aims to develop a new type of energy-efficient, reliable and location-independent handling technology based on passive vacuum generation and the development of a framework for identifying and avoiding impending sealing failures. The approach is biologically inspired and designed to operate entirely without the active supply of external energy for vacuum generation. On the basis of these developments, opportunities for significant potential savings in terms of energy use, CO_2 emissions and operating costs could be enabled.

Keywords. Vacuum handling, energy efficiency, biomimetics, Mediterranean medicinal leech, *Hirudo verbana*.

1. INTRODUCTION

Vacuum handling technologies are widely used in industrial automation due to gentle handling, high cycle rates and flexibility across object geometries [1]. As deployments scales and task diversity increases, the efficiency and infrastructural footprint of vacuum generation become critical constraints, especially in mobile and decentralised settings. The rapid growth of e-commerce and warehouse automation has significantly increased the demand for fast, flexible handling systems. Automated storage and retrieval systems and autonomous picking stations frequently rely on vacuum gripping to manage packaging materials, cartons and irregularly shaped goods [2, 3].

In conventional industrial automation, the pressure difference is commonly generated pneumatically via compressed air due to the inherent simplicity and low component costs. On mobile and decentralised platforms, however, compressed air becomes impractical: the energy density of compressed air is low, on-board air tanks are not viable for extended duty cycles, even with periodic recharging. The use of hoses to connect to the compressed air supply constrains the workspace and safety envelope. Electrical vacuum generators such as pumps or blowers require continuous electrical power and increase system complexity and noise [1, 4]. These constraints motivate the passive generation of pressure differences with the goal of creating and maintaining the pressure difference during the handling cycle without an external power supply. However, passive systems lack active pressure regulation. As a result, leakage events can erode the holding force and compromise process reliability [5, 6]. For market acceptance, passive vacuum handling must not only generate the pressure differences efficiently but also ensure high process safety. This requires minimising leakage through an innovative gripper design as well as in situ detection and avoidance of leakage events.

This paper addresses this challenge via three complementary strategies, which are developed in the following chapters. Section 2 surveys passive generation of the pressure difference and safety measures for vacuum maintenance. Biomimetic compensation concepts for enhancing the sealing and compliance are presented in section 3. Section 4 develops a process-safety framework for the detection of imminent leakage-induced failures. Section 5 concludes with an overview of the addressed challenges, future potentials and an outlook.

2. ACTIVE AND PASSIVE SUCTION GRIPPERS

2.1. General Operation Principles for Suction grasping

The operating principle of suction grippers is based on a pressure difference between the ambient pressure and the internal volume of the suction cup, which is positioned close to the surface of the handled object. When the gripper and the object are pressed against each other, the suction cup is sealed against the ambient pressure, enabling a frictional connection and the creation of a pressure difference [7]. Since handling is conventionally carried out under ambient conditions, a negative pressure must be generated inside the suction cup [8, 9].

The achievable holding force F for a given task can be defined by [8]

$$F=\Delta p \cdot A_{eff} \cdot z \cdot n \cdot \eta \cdot \frac{1}{S} \quad (2.1)$$

where $\Delta p = p_{amb} - p_i$ describes the difference from the environmental and the internal pressure, A_{eff} the effective sealed area of the gripper and z the number of grippers. The deformation coefficient n, the system efficiency rate η and the safety factor S can be used to take gripper characteristic and process-induced uncertainties into consideration. In principle, this pressure difference can be generated using two different principles, which are described as active and passive principles in the following [10].

2.2. Active Generation of Pressure Differences

The industrially established principle as the usage of "active" grippers. Here, the pressure difference is created (active suction cup [11]) by either an electric or pneumatic vacuum generator [10, 12]. These vacuum generators reduce the gas mass within the suction cup's internal volume, thereby decreasing the pressure within the suction cup. The internal volume of the suction cup can be reduced during the process of evacuation, depending on the design of the suction cup. In the case of the suction cup being designed as a suction plate, the internal volume remains constant. This indicates that the internal volume of the suction cup can be described as $V_1 \geq V_2$ and the absolute pressure as $p_1 > p_2$ [7].

2.3. Passive Generation of Pressure Differences

Another possibility is the generation of the pressure difference within a closed system, thereby ensuring a constant mass within the suction cup (passive suction cup [11], see Figure 2.1 (left)). In the "passive" applications, the pressure difference is established through the application of a force resulting in an increase in the internal volume. With this applied force and the deformation of the gripper, the internal volume of the suction cup V is enlarged and the condition $V_1 < V_2$ applies. According to the ideal gas law, this results in a decrease in the absolute pressure p within a closed, isothermal system. This pressure difference generation process, which merely results from the deformation of the gripper, is conventionally described as passive and therefore cannot compensate for pressure increases in the suction cup caused by inadequate sealing. "Passive" specifically implies that the required force F is applied by the handling device, thereby eliminating the need for an independently powered vacuum system

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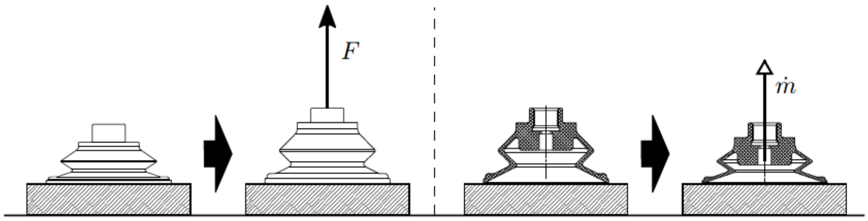

Figure 2.1. Passive vacuum suction cup – closed system (left)
and active suction cup – open system (right) [7]

In contrast to active generation of pressure difference, which relies on a continuous energy supply from pumps or compressors, passive generation of pressure difference relies exclusively on the volume change within a previously defined volume as a result of a discrete external force. For instance, the design of a passive suction gripper may take form of a clamping pivot and a slide damper (Figure 2.2). During operation, a discrete external load presses the cup onto the surface, reducing the chamber volume and expelling air. The elastic lip seals the interface, thereby creating a pressure differential that results in the cup adhering to the surface. The release process is actuated by opening the slide damper, thereby allowing the chamber to vent [8]. However, leakage cannot be actively compensated, so the holding force decays if the seal is disturbed. Consequently, the energy required to generate the vacuum is significantly lower than for an actively operated vacuum generator.

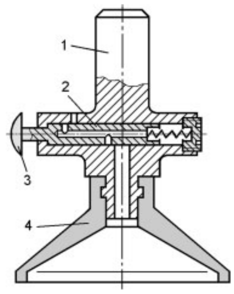

Figure 2.2. Principle of an exemplary passive vacuum design [8]
(1) clamping pivot and carrier, (2) manually operated slide damper,
(3) service button, (4) disk sucker

2.4. Use-Case: E-Commerce and Resulting Challenges

To utilise this high degree of energy efficiency, the systems have to be qualified for industrial usage. Especially the required reliability of the grasping forces is currently not achievable for all surfaces. In e-commerce fulfilment, heterogeneous items, uneven or film-covered surfaces, contamination and short cycle times increase the risk of leakage-induced detachment. Therefore, three practical challenges are focused:

(i) System-level adaptation of the pressure difference,

(ii) Suction-cup design for sealing robustness and

(iii) Leakage-aware handling strategies.

Currently, passive systems struggle with very short cycles and the majority of approaches are only capable of functioning in a leak-free manner when operating within an ideal environment. In practice, the likelihood of a small leakage in the seal of the passive suction cups during handling cannot be ruled out, raising the risk of a loss of the handled component. Existing systems have not yet been designed to compensate for this impending leakage and there is no established process setup for a proactive reduction of handling parameters such as speed or acceleration, nor a move to a safe position. Other promising approaches involve a flexible membrane that can easily adapt to the surface of a handled, which can generate sufficient pressure differences for a handling process through a small stroke to increase the volume beneath the membrane [13]. Another focus lays on concepts that minimise leakage. Soft sealing lips that adapt optimally to the respective workpieces are of key importance for this [6]. Initial concepts have been developed and implemented to combine extremely soft sealing lips with harder suction cups [1].

In the following chapters, the different possibilities (i) - (iii) are investigated.

3. Possible Safety Systems for Achieving Reliable Handling with Passive Grippers

In order to achieve the highest possible process reliability when using passive vacuum gripping systems, there are generally two possible development goals: First, the development of suction grippers with optimal sealing properties should be considered. These grippers should be designed to achieve optimal sealing with the handled components, thereby allowing the lowest possible leakage airflow into the evacuated suction gripper. If a leakage airflow eliminates the created pressure difference, the gripping force is also removed, resulting in the handled object being dropped. Secondly, an additional safety system can be employed to prevent the component from falling off in the event of high leakage, thus ensuring the continuity of the current running process without damaging the component.

The following approaches are therefore being further considered as safety systems:

- Redundant vacuum generator
  - Active, e.g. using a small electric pump
  - Passive, e.g. using a second passive suction cup or a matrix of suction cups that can compensate for the failure of a suction cup
- Additional storage volume
  - Rigid, e.g. an additional pneumatic cylinder as storage
  - Flexible, e.g. a bellows
- Additional safety element
  - Mechanical, e.g. a clamp
  - Electric field
  - Magnetic (if the workpiece is ferromagnetic)
  - Adhesive

Within this approach, this could only be achieved via a redundant pump that intervenes in an emergency. However, this would then no longer be a purely passive solution. Two implemented approaches (Figure 3.1 and Figure 3.2) can therefore only represent the starting point for targeted further developments for a leakage-robust passive vacuum gripper design.

The redundant system in Figure 3.1 consists of a high flow suction cup and an adhesive tape. For a passive holding solution, the adhesive tape mounted on the gripper will grasp the workpiece. If the holding force is not high enough or if a failure occurs, the vacuum gripper can be activated to hold the workpiece like in a standard vacuum handling application.

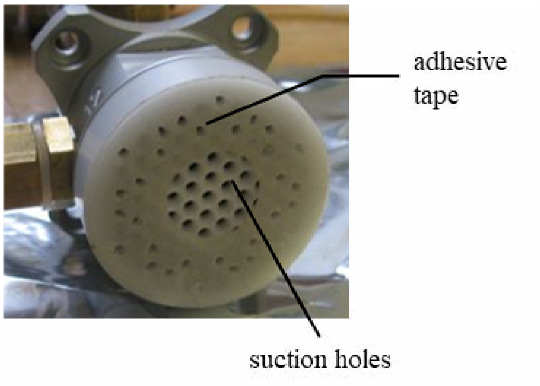

Figure 3.1. Redundant system with an additional adhesive tape that can hold the component in case of vacuum system failure

A first functional prototype shown in Figure 3.2 was equipped with a membrane, a pressure mechanism, a venting valve, a vacuum sensor, an additional pump (top of Figure 3.2) and a mechanical connection to common robot flanges. If leakage occurs during passive handling, this can be recognized by the vacuum sensor and the additional pump can be activated. Alternatively, there could be a solution with an additional vacuum realized by a pre-loaded air cylinder or a bellow.

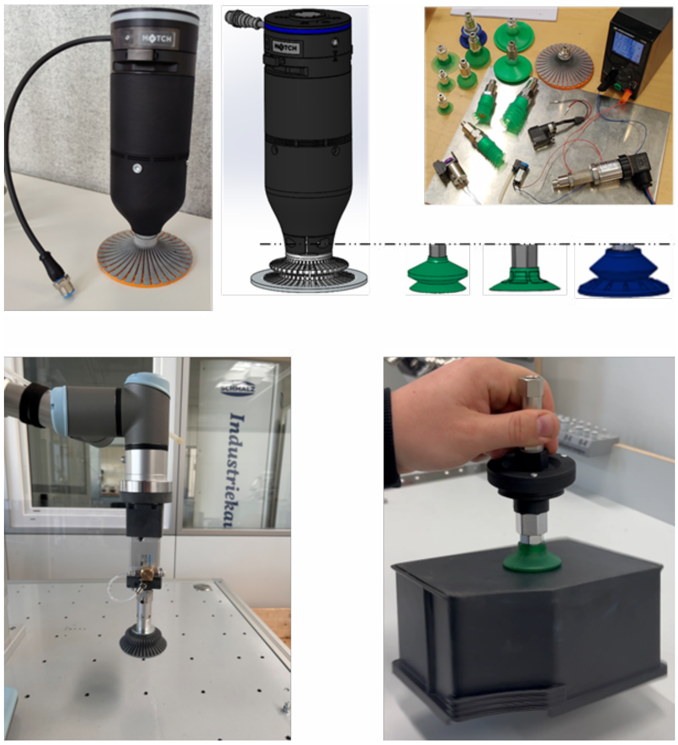

Figure 3.2. Redundant system with an additional pump (top), a system with a compressed air cylinder as a pre-loaded accumulator (bottom left) or with a flexible bellows (bottom right)

4. Leakage Compensation based on Biomimetic Principles

In biology, multiple reversible attachment mechanisms based on suction have evolved, providing engineering with a wealth of role models for vacuum-based, flow-free, energy-efficient suction devices. Most organisms utilising suction are aquatic, especially leeches are of particular interest for biomimetic approaches due to their semi-aquatic nature and ability to attach underwater as well as on land. The hematophagous Mediterranean medicinal leech (*Hirudo verbena*) evolved a remarkable mechanism to hold on the body surface of its hosts (mammals and fish), which could inspire the solution to a classical engineering problem: how to attach securely and reversibly to a wide range of substrates without the assistance of an external vacuum source. The leech accomplishes this through two muscular suction cups located at the anterior and posterior ends of its body [14], (Figure 4.1). These two suckers enable the leech to attach and move on surfaces underwater and on land that are smooth, rough, or even porous [15, 16].

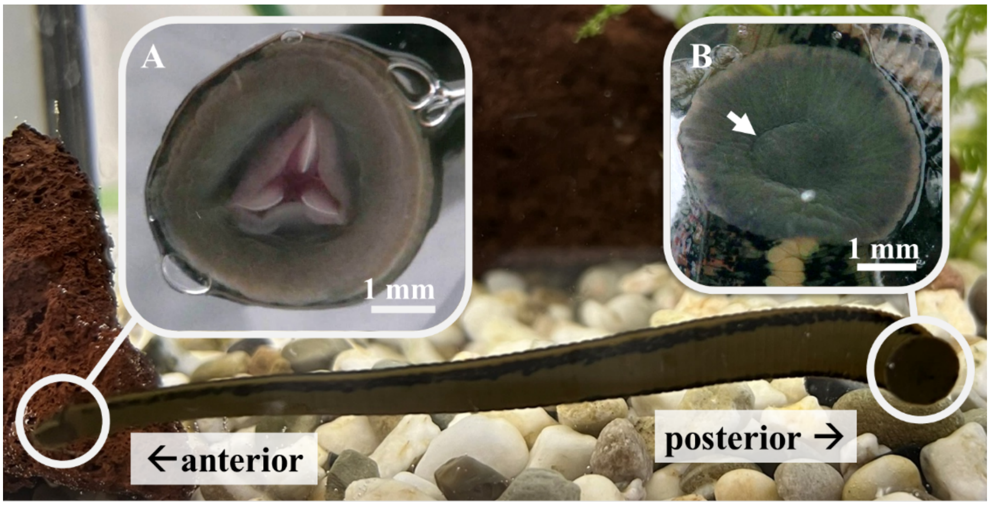

Figure 4.1. Mediterranean medicinal leech *Hirudo verbana* with its anterior (A) and posterior (B) suckers. White arrow: Grasping-like deformation of the posterior sucker.

The leech alternately attaches and detaches both suckers for locomotion (inchworm-like gait or vermiform crawling), while the anterior sucker additionally provides a stable fixation point for the jaws during feeding, i.e. blood intake [14] as seen in Figure 4.1A. For attachment, both suckers employ the same physical principle – generation of negative pressure by musculoelastic sucker deformation – yet differ in their functional design and redundancy. The posterior suction disc is exclusively used for locomotion and attachment, while the anterior sucker fulfils multiple roles in locomotion and feeding. The procedure of surface contact formation and attachment from the inside out of the suction discs is equal in both types. This process dramatically reduces the dead volume and increases the contact area with the object's surface when compared to the classical suction cup designs commonly used in industrial applications. Even though the "normal" suction performance of both suckers is already impressive, the anterior sucker can additionally actively adjust the pressure difference between the sucker chamber and the surrounding medium (water or air) via the mouth orifice in the case of an approaching leakage. Thereby, the anterior sucker reaches slightly higher attachment force maxima than the larger posterior sucker in pull-off tests, while the posterior sucker sets the pressure difference and needs to adjust to such events solely through sucker deformation and cavity sealing. [15] The latter is demonstrated in Figure 4.1B in which the posterior sucker is attached to a flexible surface and pulled, leading to a particular pronounced, almost grasping-like deformation of the sucker to generate an increased pressure difference and counter an imminent leakage. The reliable performance of both suckers demonstrates that strong, flow-free suction can be achieved without an active pump, making the leech an ideal biomimetic role model for passive, vacuum-based suction grippers.

4.1. Functional Basis of the Leech Suction System

The anterior sucker of *H. verbana* is formed by its first four body segments and the posterior sucker by its seven terminal body segments. Both suckers contain strong musculature organised in circular, radial and other orientations, as well as connective and glandular tissue. When the leech attaches with the posterior sucker, the sucker flattens and spreads over the surface, thereby increasing its contact area. The rim forms an airtight seal, while the sucker musculature enlarges the cavity volume, reducing the internal pressure. No valves or ducts are involved: all pressure differentials arise from the mechanical interplay of elastic deformation and sealing. This mechanism is inherently reversible; releasing the sucker simply involves local muscular contraction at the rim to admit air or water flows into the cavity. [15]

A defining feature of both *H. verbena* suckers is their distributed actuation: most of the sucker contact surface is controlled by fine musculature and capable of fine deformation. This allows continuous adjustment of local contact pressure and shape, providing adaptive and consistent surface contact even on rough, uneven or porous substrates. Although capillary bridging is necessary for maximum attachment forces, the attachment remains suction-dominated across many substrate conditions (even those characterised by porosity) as the leech is capable of closing surfaces cavities and holes with its highly deformable suckers. [15] The ability to maintain suction on non-airtight substrates illustrates the robustness of the system and highlights the leech’s highly adaptable attachment strategy. When confronted with objects that do not offer sufficient surface area for suction (e.g. hairy surfaces or mesh structures), the leech's ability to locally control and deform its suckers provides secondary attachment mechanisms, such as clamping, spacing and locking at object edges or into object spaces [15]. The muscles and connective tissue in the suckers that cause these unique deformation and attachment properties are anatomically derived from the tissue layers in the leech’s basic body segments. The way in which the tissues within the suckers are anatomically and functionally organised has not yet been investigated in detail. However, a complete understanding of the morphology and anatomy is a prerequisite to encoding the functional principle and abstract them for engineering.

4.2. Design Implications for Passive Suction Grippers

Both suckers, but especially the posterior one demonstrates the possibility of a stable suction through shape change and sealing alone. From this follow three critical engineering requirements for passive suction cups: 1) negative pressure generation by structural deformation, 2) minimisation of leakage and 3) delay of peel or detachment events. These are realised biologically through geometry, compliance and muscular control.

The first important aspect is negative pressure generation by structural deformation. Instead of state-of-the-art suction cups, that get deformed and attached to a surface when their dead volume is evacuated by an applied vacuum (Figure 2.1), a biomimetic passive sucker should be capable of deforming itself to generate a negative pressure difference, preceded by an initial surface contact that is as large as possible, with minimal dead volume.

The second aspect is leakage control: The rim of the leech sucker is highly compliant and structured with radial furrows. These grooves act as fluid reservoirs and distribute mucus uniformly across the contact area, forming a tortuous path for air leakage. Since an industrial requirement are residual-free handling devices, a biomimetic optimised suction gripper cannot rely on applied liquids for maximal sealing and attachment forces. Possible alternatives could be the use of materials with different stiffness and micro-patterned rims to increase the contact area and to provide a comparable sealing function without residues.

The third aspect is detachment control: In mechanical terms, failure of suction typically initiates as a peel at the sucker edge. The leech mitigates this for the posterior suction disc by a joint-like neck constriction connecting sucker and body, which allows pitch–roll flexibility and maintains uniform compression along the rim. Additionally, the secondary attachment mechanisms could inspire suckers with mechanisms that mechanically counteract the detachment of the sealing lip, prevent it altogether, or even lead to automatic re-gripping or jamming of the formerly attached object in the event of suction failure. This could be achieved through structural and material-immanent functions in the suction cup.

In sum, *H. verbana* provides a rigorous template for flow-free, purely passive suction and leakage control. The posterior sucker demonstrates that a pump-less vacuum can be generated and stabilised through geometry and sealing alone. In contrast, the anterior sucker highlights the importance of a pump as an additional fail-safe mechanism where feasible. With these elements, passive suction grippers can achieve the leech's hallmark combination of adaptability, robustness and passive attachment.

5. INCREASING PROCESS SAFETY

Passive vacuum handling eliminates the need for compressed-air infrastructure; however, it removes the ability to actively re-establish or regulate vacuum during operation. As a result, leakage caused by surface topography or off-axis loading can lead to a seal deformation and weakening and result in the detachment of the handled object. The object loss following the sealing detachment can occur within milliseconds. The early detection of the sealing deformation is therefore crucial for the purpose of either adapting the robot motion or ensuring the safe placement of the object. Therefore, the development of an integrated approach represents a potential solution for enabling passive vacuum handling technologies in industrial automation in order to establish a sufficient process safety.

Process safety in this context can be understood as the probability of completing a pick-and-place operation cycle without an occurring object loss. To prevent leakage-induced object loss, the critical moment of the imminent object detachment at the gripper-object interface has to be identified and analysed. Leakage-induces object loss can occur from a variety of sources. These can be grouped into following [3]:

- (i) Influences from the gripper characteristics, e.g. seal degradation
- (ii) Influences from the object properties such as surface roughness, load, mass eccentricity or surface contamination
- (iii) Process-induced influences, e.g. shear load spikes during acceleration or jerk as well as off-axis loading during the pick process and transport phase.

In order to react to an imminent object loss, it is necessary for the detachment to be detected in advance. This results in the need of a sufficient holding force level to be able to ensure the object is being attached to the gripper for the required time between the detection and potential reaction strategy.

5.1. Empirical Characterisation and Derived Optimisation Potential

In the following, the behaviour of the sealing detachment and resulting leakage is investigated. Especially the sealing itself is focussed, therefore the influences from the gripper (i) and object characteristics (iii) are reduced as much as possible. For this purpose, systematic static pull-off experiments were performed with a 7-axis robot on a smooth, non-porous surface using a standard bellows suction cup (FG 62 NBR-55 N018 from Schmalz) functioning as a passive gripper to initially derive the main process-induced effects (iii). For these experiments, an in-cup pressure sensor was integrated into the suction cup setup to obtain the internal suction cup pressure $p_i(t)$. Furthermore, a 6-DoF force/torque transducer located at the robot flange captured the occurring load, while an ultrasonic distance sensor measured the end-effector extension along the surface normal (Figure 5.1).

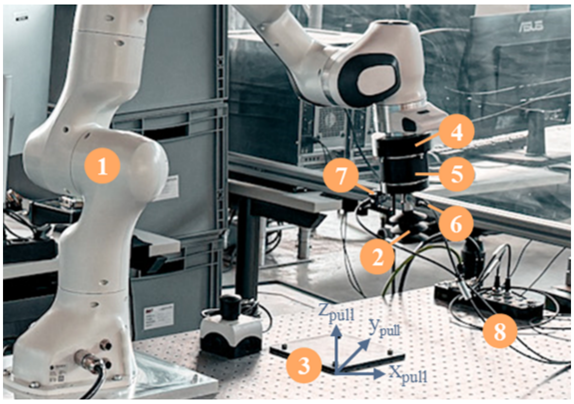

Figure 5.1. Experimental setup
(1) robot arm, (2) bellow suction cup functioning as a passive gripper,
(3) PLA plate, (4) flange adapter, (5) force transducer, (6) vacuum sensor,
(7) ultrasonic sensor, (8) IO-link master

Within the experimental investigation, the approach depth, approach angle, process speed and acceleration for linear motion were varied by the factorial experiments. The process depth is defined as the distance from the ultrasonic sensor to the pull-off surface with a maximum possible compression d_{max} with approx. -20 mm for the depth value compared to the initial undeformed state of the suction cup. The approach depth influences the deformation and sealing and the loads to the sealing lip as well as the handling object. The velocity and acceleration were varied as a percentage of the maximum robot speed and acceleration to investigate the influences on the sealing and release behaviour through occurring dynamic effects, e.g. viscoelastic effects. The variation of the rotational angle between the gripper verticals and the surface normal was varied within the range of $w \in \{-20°, 0°, 20°\}$ to examine its impact on the sealing behaviour and force distribution.

The investigated response variables were the measured internal pressure difference, the pressing force applied to the sealing to the surface as well as the pull-off force. The experiments were performed with 20 process variable combinations, each with n=50 trials (see Table 5.1). For each parameter combination, the maximum level of pressure difference and the minimum and maximum vertical force values were measured and averaged across the repetitions. To unify the sampling rate, the lower-rate vacuum data was anti-alias filtered and resampled to 150 Hz to match the force sampling rate. Due to the data acquisition of the vacuum and ultrasonic sensor via IO-Link-master and TCP/IP, a delay in the data stream compared to the USB-based force/torque data may occur. To avoid this distortion in the temporal overlap of the various data sources, an initial pull-off movement was performed before each trial to align the data streams by an offset correction based on the first prominent peak during the start-up motion, compression and pressure establishment.

The initialisation phase is characterised by a contactless interaction between the suction cup and the pull-off surface. The robot approached the surface orthogonally without any load besides the end effector setup consisting of gripper as well as cables and without cup deformation or pressure change (F_Z=$p_i(t)$=0) (Figure 5.2 (a)). The behaviour of the vacuum gripper during the pull-off experiments could then be segmented into three phases (Figure 5.2 (b)-(d)):

- Sealing phase,
- Leakage onset,
- Contact rupture.

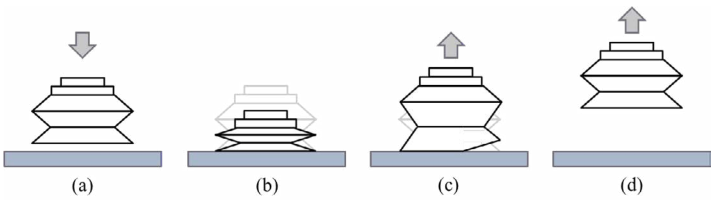

Figure 5.2. Phases of the pull-off experiments
(a) contactless phase, (b) sealing phase, (c) leakage onset due to local occurring sealing detachments, (d) contact rupture leading to complete sealing detachment

During the approach to the defined approach depth, the normal force -F_Z occurs, leading to a sealing lip deformation, thereby sealing the gripper to the pull-off surface. When a positive pull force is applied, a pressure difference in the gripper leads to an adhesion of the seal to the surface until the collapse of the holding force $+F_Z$ at contact break. After release, the gripper and kinematic structure exhibit a short elastic ring-down (Figure 5.3). These phase markers provide consistent anchors for feature computation.

Table 5.1. Section of the performed factorial pull-off experiments

No.	v_{robot}	a_{robot}	w [°]	Δp_{max_avg} [mbar]	$F_{Z\_min\_avg}$ [N]	$F_{Z\_max\_avg}$ [N]	$\sigma(p_{max\_avg})$ [mbar]	$\sigma(F_{Z\_max\_avg})$ [N]
1	50%	50%	0	451.72	-39.65	57.64	16.91	4.52
2	100%	50%	0	475.21	-38.17	59.42	22.17	4.27
3	50%	100%	0	477.18	-39.37	56.13	24.8	7.64
4	100%	100%	0	495.65	-39.61	56.71	19.94	9.41
5	50%	100%	20	432.93	-37.58	66.92	9.41	4.1
6	100%	50%	20	454.20	-43.82	72.24	1.78	1.58
7	100%	100%	20	440.81	-44.31	69.58	3.12	1.14
8	50%	50%	-20	393.20	-57.69	63.51	14.15	2.57
9	100%	100%	-20	375.98	-58.35	58.46	24.82	5.07
10	50%	100%	-20	391.83	-58.79	64.06	11.01	1.93

Over the 50 repetitions for each parameter set, the standard deviation remained comparatively small in relation to their respective means, thereby signifying a high degree of repeatability. Varying the initial movement as well as the pull-off speed and acceleration showed negligible effects in the tested static conditions due to short distances and therefore short acceleration distances, though dynamic trajectories are expected to introduce viscoelastic and inertial effects.

The impact of a varied approach angle was demonstrated and indicated, that non-orthogonal approaches reduced maximum pressure difference by 15-25 % due to asymmetric sealing. An orthogonal approach has been demonstrated to achieve the highest average pressure difference values, while average pull-off forces F_{Z,max_avg} show a slightly higher level at w=20°. This discrepancy can be attributed to the fact that the achievable holding force is also dependent by an angle-induced pre-compression, which is described with the deformation coefficient n. A tilted approach has been shown to increase local lip compression and bending stiffness. It has been observed that the strongest average contact force occurs at a negative approach angle, indicating a higher pre-load which influences the initial sealing behaviour while achieving a lower pressure difference. Therefore, the selection of approach angle should be dependent on the specific characteristics of the surface and the task. Research in future will focus on the quantification of the trade-off between angle-induced precompression and maximum cavity pressure difference with the aim of deriving task-adaptive approach strategies.

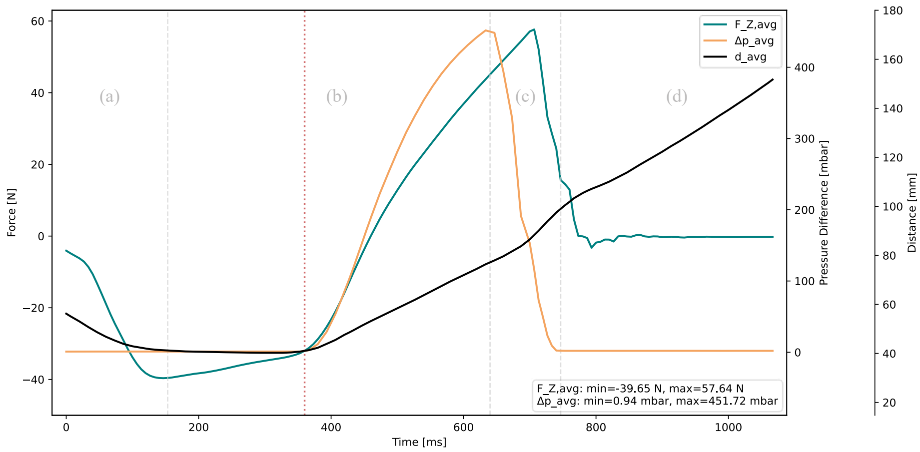

Figure 5.3. Plot of average force in Z-direction, pressure difference and distance values divided into the phases of the pull-off experiment (grey dashed lines) pull-off experiment no. 1, pull-off at t_{pull}=$360ms$ (red dotted line)

6. Conclusion and Outlook

The overall goal of the presented publication was the investigation of energy efficient handling systems with a focus on passive suction grasping. However, even though the usage of a passive suction cup is a very energy efficient solution to decrease energy consumption, process safety topics such as system failure and the possible loss of the workpiece must be considered. As a result, the three different aspects of achieving reliable grasping with passive grippers were investigated, derived from a use-case of a usage in short-cycle e-commerce handling tasks. Next to systemic safety concepts, biomimetic-inspired suction designs were focussed. Additionally, redundant safety strategies and mechanisms were investigated to enable a wide range of possible applications in automated processes.

Overall, the findings highlighted the possibilities and possible further research avenues for passive suction grippers to achieve industrially acceptable reliability. As a next step, the highlighted research avenues should be analysed further and combined into prototypical functional demonstrators, to empirically investigate possible process limitations. Additionally, modelling and simulation approaches could significantly accelerate development processes for passive vacuum handling systems and should be researched alongside physical demonstrators. Overall, the passive handling technology can be described as an emerging technology with a high potential for various use-cases. If a high degree of reliability can be achieved, significantly enhanced efficiencies for automated handling systems are opened up for various industries. Additionally, elements of these approaches could also be transferred to conventional vacuum handling technologies, opening up further potential for increased energy efficiency.

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