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Suction Helps in a Pinch: Improving Underwater Manipulation with Gentle Suction Flow

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***Abstract*— Pinching is an important capability for mobile robots handling small items or tools. Successful pinching requires force-closure and, in underwater applications, gentle suction flow at the fingertips can dramatically improve the handling of light objects by counteracting the negative effects of water lubrication and enhancing friction. In addition, monitoring the flow gives a measure of suction-engagement and can act as a binary tactile sensor. Although a suction system adds complexity, elastic tubes can double as passive spring elements for desired finger kinematics.**

I. Introduction

The study of wet or underwater manipulation is important for applications ranging from oceanic exploration to surgical robotics. For underwater operation, robots can provide access to coral reefs without the dangers and difficulties of extensive scuba diving. This study is motivated by an ongoing collaboration[1] to enable marine biologists to conduct research on coral in the Red Sea through a remotely operated dexterous robot.

Marine environments are highly unstructured, and dynamics of underwater operation can make it very difficult to operate successfully. Fluid interactions between an object and the hand can prevent acquisition by pushing the object away. Friction also typically decreases due to water lubrication. In previous work it was shown that gentle suction flow at the fingertips is helpful during object acquisition not only because of the attractive force, but also for mitigating disturbing flows when approaching light targets [1]. This paper explores the effect of light suction flow after acquisition; suction influences the hand's ability to retain objects through increased friction and normal forces. In some cases, suction can provide stability to otherwise unstable grasps. This work can guide application-specific design and sensing choices concerning the addition of suction hardware for underwater hands.

Hand research for underwater archeology or industrial applications, such as [2]–[4], focuses primarily on the design, control, and sensing of the hand to achieve various important grasp types while withstanding the harsh environment, including high ambient pressures at large depths. To our knowledge, none of these submersible applications has incorporated light suction flow as a way to enhance object acquisition and retention with a multi-fingered hand.

[1]The Red Sea Exploratorium includes collaborators from King Abdullah University of Science and Technology (KAUST) Red Sea Research Center, Meka Robotics, and Sanford University.

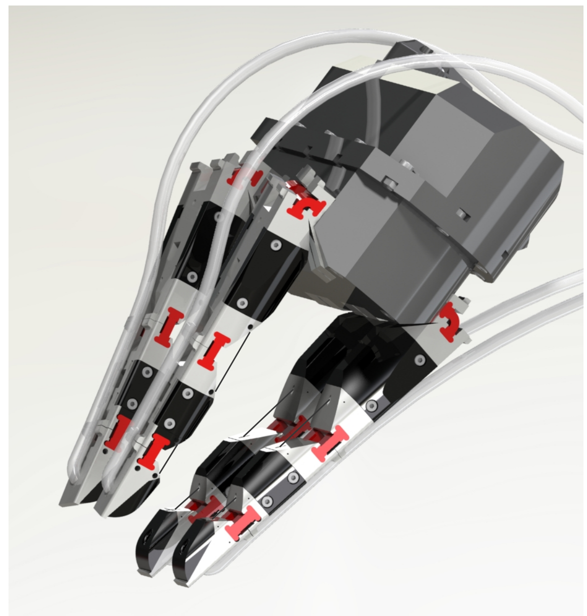

Fig. 1: A four-finger hand, developed for the Red Sea Exploratorium, uses underactuated fingers equipped with gentle suction to improve grasp stability. This hand is designed for power grasping, but can also perform secure pinches with the help of suction flow at the fingertips.

Medical devices sometimes include suction cups mounted to small, elastic grippers that apply gentle surface forces on relatively large, wet, and slippery organs [5]; these grippers focus on delicate manipulations of biological tissues. Marine exploration requires manipulation capabilities that extend beyond those of suction cups. A multi-fingered hand is better suited for a range of tasks that include power grasping large objects and tools as well as pinching small objects. Although there is ongoing work to make suction cups apply large forces on various substrates [6]–[8], artificial suction cups are still limited to smooth nonporous surfaces as compared to their biological counterparts [9,10]. Low pressure suction flow can work with rough and porous materials, and is also utilized to acquire objects in nature [11].

Other investigators have noted that manipulation in air can also benefit from fingertip suction; a light attractive force on the fingertips allows the hand to perform new maneuvers with light objects [12]. However, water is approximately 56 times more viscous than air, making the benefits of suction flow in water significantly more pronounced. This paper seeks to characterize how fingertip suction flow benefits the quality

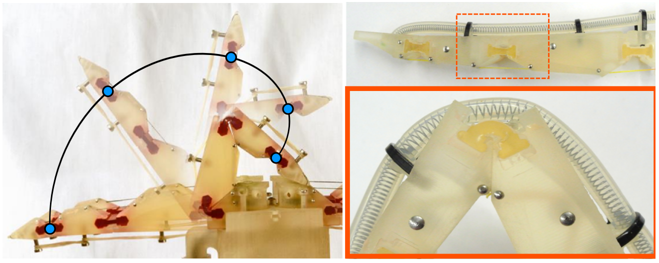

Fig. 2: Left – Passive springs determine finger kinematics. Right – Tubes route suction to the fingertips, while doubling as spring elements. A spring inside the tube keeps it from collapsing as the knuckle closes.

of underwater contact.

Pinching is an essential grasp type for acquiring marine samples. It enables a manipulator to acquire objects from challenging positions, like inside a crevice or on a flat surface [13], and manipulate objects with precision [14]. Previous work has found that suction flow is particularly helpful during the acquisition of light objects [1]. Many light objects also tend to be small, therefore pinching is the primary grasp type studied in this paper to characterize the role that gentle suction flow can play. The findings about suction flow may then be extended to more complex grasp types.

II. Finger Design

A. Suction Integration

The hand used for this work is underactuated, with compliant flexure joints, a solution which has been successful for highly unstructured environments and tasks [15]. Usually the passive mechanics of an underactuated finger are determined by the linkage, flexure, or spring design [16]. In our previous hand design, we used elastic bands that nonlinearly decreased moment arm throughout range of motion to approximate a constant-force spring with pre-load [1]. However, suction tubes can double as passive springs to alter joint stiffness (Fig. 2) and allow for compact incorporation of suction tubes along the fingers.

A compression spring inside the tube keeps it from necking when the joint closes. The hysteresis of the silicone tubing and spring system is similar to other rubber spring materials used for passive finger elements.

The pump used for this study has a flow rate of 4 L/min and a blocked pressure of 0.6 atm. The two very soft silicone rubber suction tubes used to outfit the fingers are 80 cm long and with a 4.76 mm inner diameter.

B. Tension Sensing

Measuring fingertip contact normal force allows for the investigation of suction effects on pinching success. A major component of the contact force is internal grasp force due to motor actuation. Therefore, these tendon-driven fingers incorporate tension sensors designed for underwater operation (Fig. 3). The tendon is routed over a dowel pin fixed to a carbon fiber cantilever, which deflects with increasing tendon tension. A disk magnet (K&J D201, 1/8"x1/32") is fixed to the end of the cantilever, and a Hall effect sensor

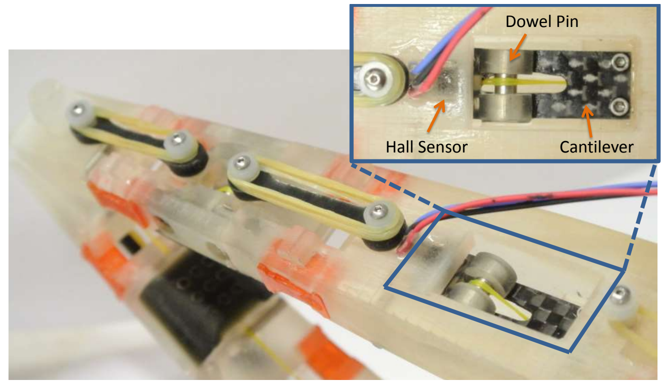

Fig. 3: The tension sensor is designed into the proximal phalanx of the finger. A Hall effect sensor measures the deflection of a magnet attached to a carbon-fiber cantilever beam.

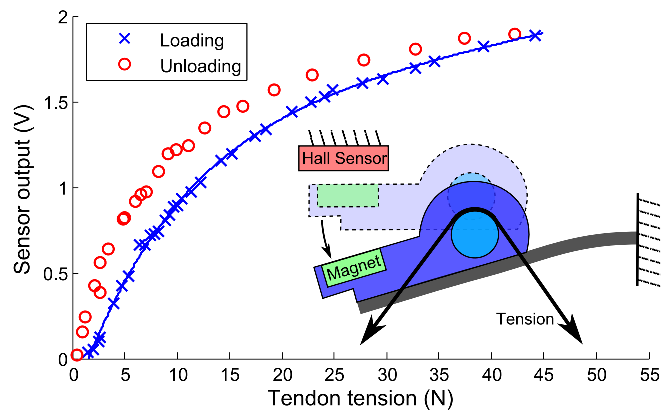

Fig. 4: Empirical tension sensor data. There is some hysteresis; a curve fit to loading data is used for calibration.

(Allegro A1324) is attached above it on the finger and coated in epoxy. The Hall effect sensor measures tension as a function of magnet displacement (Fig. 4). Although there is some hysteresis due to the flexing of the carbon fiber beam and tendon friction, the calibrated loading curve provides a useful measure of the tendon force as the fingers close. The actuated pinch force can then be estimated using a model for the nonlinear finger compliance and tendon geometries, as described in [1].

III. Modeling Fingertip Contact with Suction

The tribological interactions between surfaces underwater with suction flow are complex. We seek to extract the features necessary to evaluate the effectiveness of light suction in the context of robotic pinching. We note that the effectiveness of pinching may be significantly altered by object curvature and surface angle (which in this study is related to the size of the object) and material properties.

Figure 5 shows two fingers pinching a trapezoidal object. Given measured values for the friction coefficient between the fingertip and a given material, the maximum vertex angle, α, can be predicted using a quasi-static model. For simplicity, it is assumed that normal force, $\overrightarrow{N}$, tendon actuated contact force, $\overrightarrow{F_a}$, suction attractive force, $\overrightarrow{F_s}$, and friction force, $\overrightarrow{F_f}$, act at one point located at the center of the suction contact

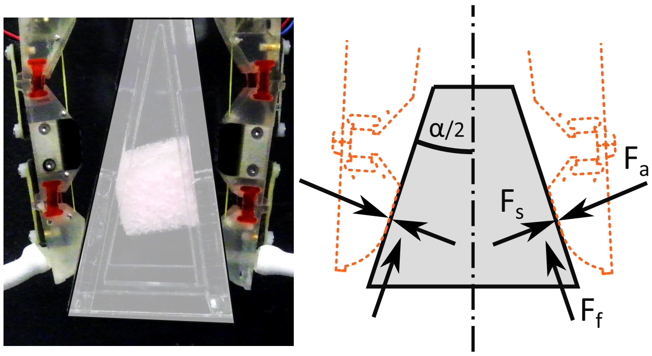

Fig. 5: Left – An underwater two-finger pinch of a neutrally buoyant object with suction. Right – Free body diagram of the pinched object.

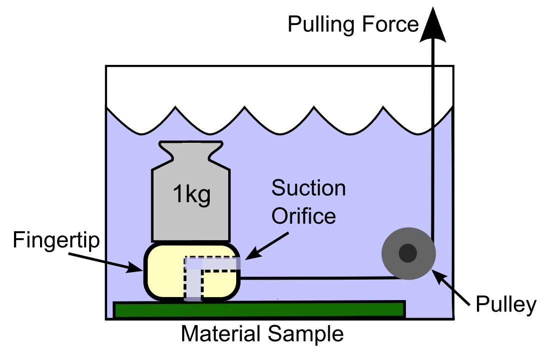

Fig. 6: Test setup for measuring friction properties in air and water. The tank was emptied for in-air trials.

patch. It is also assumed that the object is neutrally buoyant, so gravity and buoyancy forces are neglected. In practice, $\overrightarrow{F_s}$ is typically small (1.2 N or less).

The normal force is the sum of the pinch force due to motor actuation and fingertip suction reaction force:

$$\overrightarrow{N} = \overrightarrow{F_a} - \overrightarrow{F_s} \tag{1}$$

Therefore, the following condition must be true to maintain a pinch on an object:

$$|\overrightarrow{F_a}| sin\left(\frac{\alpha}{2}\right) \leq |\overrightarrow{F}_{f,max}| cos\left(\frac{\alpha}{2}\right) \tag{2}$$

After substituting $|\overrightarrow{F}_{f,max}| = \mu|\overrightarrow{N}|$, where μ is the coefficient of friction, the equation simplifies to:

$$tan\left(\frac{\alpha}{2}\right) \leq \mu\frac{|\overrightarrow{N}|}{|\overrightarrow{F_a}|} \tag{3}$$

where the friction coefficient may change with respect to suction and actuation forces:

$$\mu = f(\overrightarrow{F_s}, \overrightarrow{F_a}). \tag{4}$$

Equation 3 can be used to calculate critical object vertex angles at which the pinch may fail. With suction, equation 3 is a function of actuation force. However, without suction, equation 3 becomes purely geometric. Near the critical object vertex angle, small disturbances can lead to premature pinch failures. We can get a sense of pinch stability by comparing this ideal model with experimental pinching results.

IV. Experiments and Results

Humans continuously monitor fingertip friction in pinching tasks [17]. Improving friction can make pinching significantly more reliable. Therefore, experiments in this study characterize the effect of water lubrication and improved traction with suction for our fingertip design.

Smooth acrylic and 1500 grit waterproof sandpaper are chosen as materials with different friction properties. Although these two materials do not encapsulate the full variety of objects found in marine environments, they do allow us to start investigating how suction flow effects change with two very different textures.

A. Characterizing Friction in Air and Water

An acrylic plate, or an acrylic plate coated in sandpaper, is placed below a weighted 3D-printed fingerpad, as shown in Fig. 6. Static coefficients, μ_s, are calculated with the minimum loading force to move the fingertip using a hand-held force scale. Dynamic coefficients, μ_d, are found from the friction force measured by a load cell attached to the base of the actuator pulling the object at a slow speed. Normal force was applied to the sample by a 1kg weight. Averages from 5 trials of each configuration are reported in Table I.

TABLE I: Friction coefficients in air and water (average of 5 trials ± standard deviation represented as a percentage of the average)

	Acrylic		Sandpaper	
	Static	Dynamic	Static	Dynamic
Air	0.51 ±3.9%	0.21 ±4.7%	0.85 ±6.0%	0.56 ±6.0%
Water	0.34 ±5.8%	0.20 ±5.9%	0.76 ±4.3%	0.58 ±1.5%

Thin-film water lubrication likely reduces contact between the substrate and 3-D printed fingertip, causing a decrease in μ_s in water.

B. Underwater Friction with Suction

In the context of robotic grasping, empirical friction estimates can capture the trends of suction flow in water. The test setup shown in Fig. 6 is used for friction experiments with suction by connecting tubes to the open orifices and changing the applied normal force. Results for acrylic are presented in Fig. 7.

The normal force, used to calculate μ_s and μ_d, is a function of both the suction force and the force due to the applied weight. The suction force was measured at varying times throughout these experiments and averaged 1.15 N. Experimental error bars represent the standard deviation of at least 5 samples. Static friction is higher with suction but does not change significantly with normal force. Interestingly, dynamic friction, μ_d, did not vary significantly with normal force or suction. Although suction improves the static coefficient in water, it is still lower than in air (μ_s averages 0.33 in water, 0.40 with suction in water, and 0.51 in air).

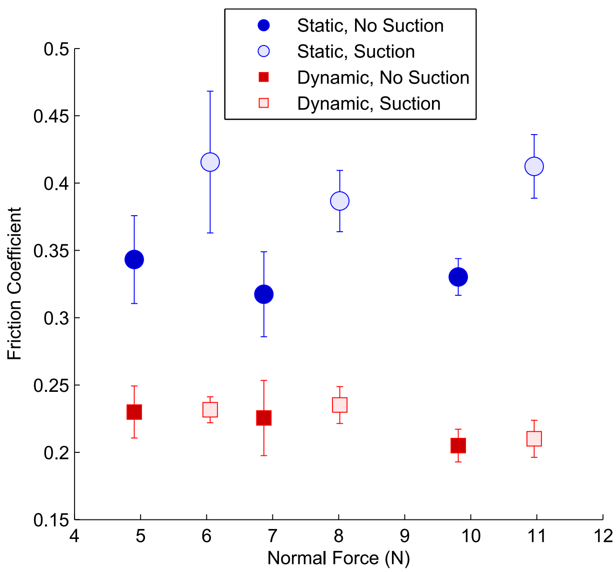

Fig. 7: Empirical static and dynamic friction results for acrylic in water, with and without suction.

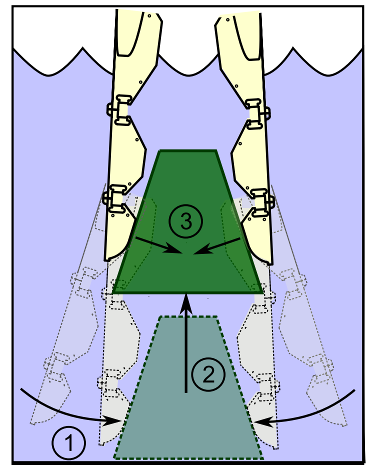

Fig. 8: Pinching experimental procedure. 1) The fingertips are closed flat on the object surface. 2) They apply a gentle grasp force ≈1N and attempt to lift the object. 3) If lifting succeeds, the grasp force is increased incrementally, while tendon tension is recorded, until the pinch fails.

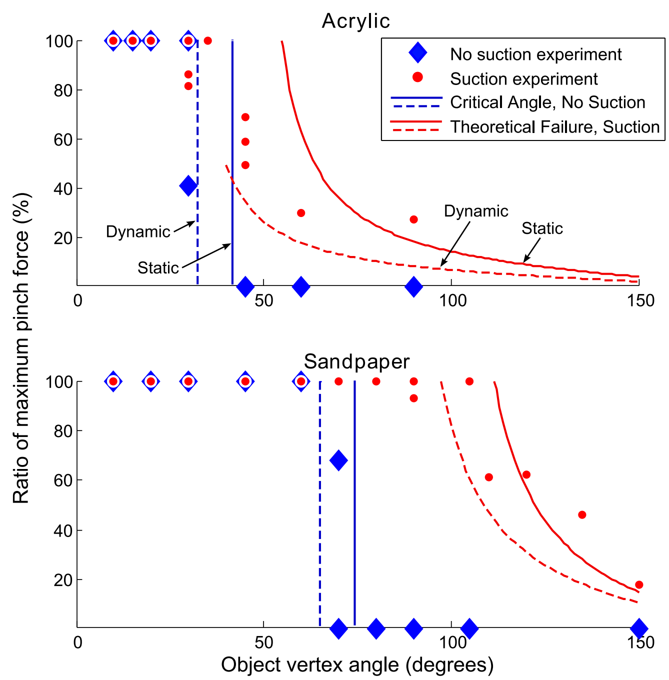

Fig. 9: Empirical pinching data is compared with static and dynamic models derived from eq. 3, denoted as solid and dashed lines respectively. See text for feature explanation. The success of a pinch changes with object vertex angle, grasp force, and material properties. The dynamic coefficient of friction models are more conservative than the static friction models.

C. Pinching Application with Suction

This study explores how improved friction can benefit robot pinching, with both acrylic and sandpaper. As shown in Fig. 8, a neutrally buoyant triangle, with varying vertex angles, α, is placed at the bottom of a water-filled tank. The hand attempts to lift the object with a small normal force, ≈1 N, with the fingerpads flush to the surface. If the object slips out, the trial is repeated; if it slips again, that point is called a 0% pinching force failure. If the object is successfully picked up, the grasp force is incrementally increased while recording tendon tension until the object slips or the motor stalls (for 100% pinching force at 280 mNm motor torque). Only points with a measured tendon tension over 3N are recorded because tension sensor readings below this value are unreliable. If at any point the object slips, even if it recovers, it is called a failure because the fingers are not in the original configuration anymore. The results of initial tests are shown in Fig. 9.

The model described in Sec. III is used to calculate the ideal critical failure angles for both no-suction and suction cases. The critical failure vertex angle without suction calculated with μ_d is lower than the one calculated with μ_s. These are vertical lines because failure is independent of normal force. The theoretical failure line with suction, computed with equation 3, using μ_d is also more conservative than the one calculated with μ_s. This is a trend line because normal force is a function of both suction force and actuated fingertip force. The suction force contribution diminishes with increased grasp force.

The friction coefficient values are taken from Table I and Figure 7. Sandpaper friction coefficients with suction were separately characterized ($\mu_s \approx$ 1.0-1.2, $\mu_d \approx$ 0.9-1.0). For objects with larger vertex angles, the hand must open more to make the fingertips lie flush to the surface, and therefore the objects are larger. Geometric nonlinearities of the proximal joint tendon and extension springs are taken into account when calculating the actuated force transmitted by the tendon using the model described in [1]. Due to these nonlinearities, 100% pinching force is around 5.5N for small object vertex angles, but 3N for objects with large vertex angles.

Without suction, near the critical angles, any disturbance can cause the pinch to fail, so it is difficult to reproduce static predictions with the experimental setup. In fact, for acrylic, the dynamic friction no-suction model is more representative of the data than the static model.

In both material cases, suction increases the maximum vertex angle this hand can successfully pinch. It is able to pinch at a 100% grasp force at 35° for acrylic and 105° for sandpaper with suction, which are improvements over 30° and 60° without suction respectively. The dynamic and static prediction lines capture the general trends observed with suction, bounding most of the experimental data. At large object vertex angles, the hand must pinch the object with lighter grasp forces.

While running the experiments, it was difficult to ensure that the fingertips were flat against the object surface. This means that for some trials, suction normal force was likely less than 1.15N (this would also be the case in normal working conditions). The sandpaper was only glued at the edges, so flexing of the surface material could conform to the orifice better than with acrylic. Measuring flow rate through the suction tubes would be helpful in future pinching experiments to account for suction engagement. Also, the motor command increments sometimes disturbed the pinch – if incremental step size was increased too much, actuation induced early failures. These non-idealities represent real-world pinching conditions. Characterizing stability and disturbance rejection will be a part of future work.

D. Suction Flow Measurement

Flow in a suction tube decreases when an object obscures the orifice. The amount of decreased flow may be a function of various factors including object roughness and porosity, how flush the fingertip is with the surface, or fingertip distance to the surface. Therefore, measuring suction flow in the tube gives a sense of the suction engagement. During pinching experiments, it is difficult to see by eye if the flat surface of the fingertip is aligned with the surface of the object. Therefore, a differential pressure transducer is added to the suction line, located near the fingertip, and its signal is compared to curling fingertip misalignment (θ shown in Fig. 10). A differential pressure transducer is chosen because it is insensitive to changes in ambient pressure and is therefore insensitive to water depth.

The results from the maneuver displayed in Figure 10 show a couple of key features. First, the differential pressure transducer gives a relatively consistent signal when the finger is at rest, without contact. As the finger starts to move, the pressure signal increases slightly (a). Initial contact with the surface can be seen in the signal at point (b), and then as the fingertip face aligns with the object surface, the signal continues to drop to zero (no-flow conditions). As the finger curls, there appears to be a monotonic relationship between θ and differential pressure, and the pressure transducer picks up small peaks as the finger sticks and slips dynamically (c). The transducer reaches a no-contact signal at $\theta \approx 22°$ (d). Finally, when contact is broken, the water dynamics of the suction system are picked up as a spike in pressure at (e) before returning to the no-contact signal.

These features are useful in the context of underwater pinching. Therefore, this suction sensor has the potential to monitor contact conditions. At a basic level, this sensor is reliable as a binary contact sensor.

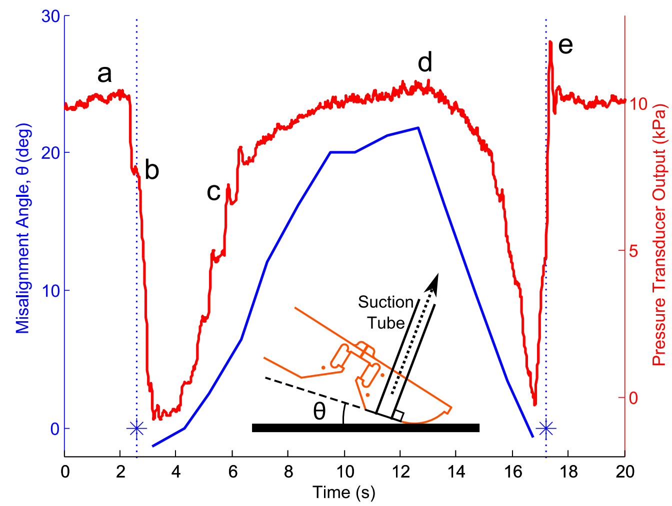

Fig. 10: Timeline shows differential pressure transducer signal (in red, with labels (a)-(e)) and θ (in blue) over time. θ was measured from a video recording of the contact maneuver at 1.02 s intervals. During the maneuver, the finger was brought flat against the surface, curled up so that theta increased, un-curled, then pulled off of the surface. The first $*$ indicates first contact and the second $*$ indicates last contact between any part of the fingertip and the surface.

V. Discussion

Suction improves static friction and subsequently reduces the need for high internal forces to successfully pinch an object. This means that suction helps to acquire small objects as well as retain very large objects that cannot be wrap grasped. Furthermore, the hand is able to pinch more objects at maximum grasp force. Monitoring pinching force and suction flow may be particularly useful when employing suction flow, to ensure that a desired fingertip/object alignment is achieved, and to avoid excessive grasp forces. Interestingly, the benefit of suction is significant for rougher surfaces, like sandpaper, as well as slippery surfaces.

A. Implementation Considerations

There is a tradeoff associated with adding suction into a design; it can add complexity and weight to the robot end-effector. However, there is a clear benefit for pinching. This work can guide the choice to add suction flow into an underwater hand design. If target objects will be relatively large or light, suction flow can make the grasp more secure in addition to facilitating object acquisition.

For applications that would benefit greatly from suction flow, there are ways to mitigate the bulkiness of incorporating suction tubes. For the finger design presented in this work, the tubes can double as passive spring elements to achieve the desired motion characteristics of the fingers. Although having suction orifices at the fingertips makes direct tactile sensing a challenge, it is possible to monitor the flow through the suction tubes with differential pressure transducers. These sensors have the potential to provide interesting tactile features, such as stick-slip occurrence, as well as indicating the quality of suction engagement.

VI. Conclusion

Pinching is a common grasp type used in acquiring objects of various sizes. It can be especially useful for underwater exploration robots when performing tasks such as capturing samples of coral and picking up small, or large, potentially slippery objects. This work demonstrates that suction flow helps by increasing the static coefficient of friction and normal force for both smooth and textured surfaces. The pinching failure prediction using experimental friction estimates adequately describes the general trends of pinching success with and without suction in water. These results can guide future work in design and control of robotic hands with light suction flow.

A. Future Work

There are many exciting pathways in which to continue exploring suction flow in the context of underwater robot grasping. It is possible that other grasp types would be improved by gentle suction flow, and subsequent new suction orifice locations could be explored. More comprehensive characterization of the differential pressure transducer signal would also allow us to use it in future experiments characterizing contact reliability and stability. It may also lead to underwater pinching control with suction to improve success and failure prediction.

The fingers in this study use open orifices at the fingertips. In dirty applications, a mesh would help prevent clogging of the pump with sand and other sediment. When the mesh starts to become clogged, the pump can briefly be reversed to flush it. Future work may characterize the impact of clogging on suction flow reliability.

The ultimate goal of this project is to allow a teleoperator to successfully interact with a marine environment. Future work will include evaluating teleoperater interaction with a robotic hand utilizing suction flow, and finding effective ways to portray contact quality information to the operator's visual and haptic console.

Acknowledgments

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