High Force Density Gripping with UV Activation and Sacrificial Adhesion

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***Abstract*— This paper presents a novel physical gripping framework intended for controlled, high force density attachment on a range of surfaces. Our framework utilizes a light-activated chemical adhesive to attach to surfaces. The cured adhesive is part of a "sacrificial layer," which is shed when the gripper separates from the surface. In order to control adhesive behavior we utilize ultraviolet (UV) light sensitive acrylics which are capable of rapid curing when activated with 380nm light. Once cured, zero input power is needed to hold load. Thin plastic parts can be used as the sacrificial layers, and these can be released using an electric motor. This new gripping framework including the curing load capacity, adhesive deposition, and sacrificial methods are described in detail. Two proof-of concept prototypes are designed, built, and tested. The experimental results illustrate the response time (15-75s depending on load), high holding force-to-weight ratio (10-30), and robustness to material type. Additionally, two drawbacks of this design are discussed: corruption of the gripped surface and a limited number of layers.**

***Index Terms*— Mechanism Design, Manipulation**

I. INTRODUCTION

Gripping devices that enable mobile robots to exert forces on their surrounding environment provide new abilities such as manipulation, use of tools, perching, and anchoring. However, grippers for mobile systems have substantially different requirements than manipulators designed for fixed-base robotic arms. End effectors for mobile robots are limited to the maximum carrying weight and battery life of the vehicle, driving the need for lightweight, high force density grippers. In addition, mobile robots may also need to operate in different environments with a range of materials; therefore, invariance to surface properties is valuable.

The robotics community has made great advancements in manipulator design; however, many existing approaches are not well suited to mobile robots in unstructured environments. Specifically, the ability to achieve high force density grasping on a range of surfaces remains difficult. Servo driven actuators are often heavy and may require certain surface geometry. Electrostatic adhesion applies gripping force between induced surface charges and electrodes, which require little to no power once switched on [1]–[5]. While these systems are lightweight and efficient, they require high voltage to produce adequate adhesion. Suction grippers have the ability to grasp delicate objects and have low holding power input, but they work best with flat or lightweight objects and require a heavy vacuum pump [6]–[8].Vacuum jamming grippers are capable of gripping a wide range of surface geometries; however, they struggle with porous materials and also require a vacuum pump [9]–[12]. Lightweight, bistable reflexive grippers have also been designed, which require no holding energy, but have only been shown to work with a suitable handhold to wrap around [13]. Gecko-inspired dry adhesives have been used in several designs; however, these typically work best under shear stress and dust may interfere with adhesion [14]–[18].

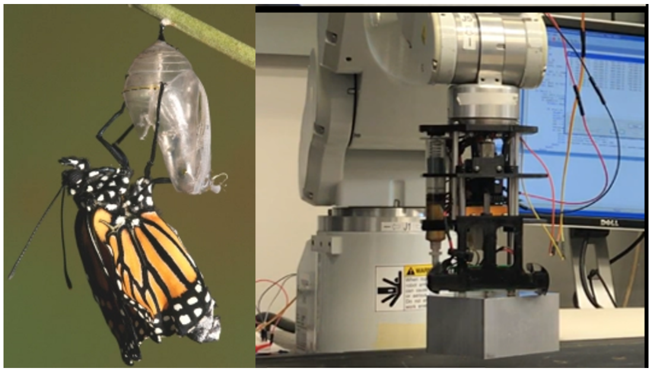

Fig. 1. Monarch butterfly discarding shell through molting [19] (Left). Robot arm adhered to payload via sacrificial layer (Right).

In this paper, we present a new framework for employing chemical adhesives in robotic gripping. Our approach draws loose inspiration from the biological molting mechanism. Molting is used in nature to discard a layer that is no longer needed. One example is when a butterfly caterpillar forms a silk pad to attach to a structure and then discards it after metamorphosis [20]. We utilize a similar approach where a robot can strongly adhere to an object and leave a sacrificial layer behind, rather than using excessive power to break the bond. Our new framework combines a controllable chemical adhesive with a stock of disposable sacrificial layers to allow a release from the permanent bond. An illustration depicting natural molting (butterfly) and engineered molting (our sacrificial gripper) is provided in Fig. 1.

The core contributions of this work include formulat-

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ing multiple frameworks for utilizing controllable chemical adhesion for grasping, and experimentally characterizing sacrificial adhesive gripping performance. In addition, we design and demonstrate a fully functional prototype that can be integrated into a range of robots and is capable of high force-to-weight ratio behavior on several diverse materials. To the best of our knowledge, this paper is the first to use controllable chemical adhesives in combination with sacrificial layers for robotic grasping.

In order to achieve controllable adhesion, we combine UV sensitive acrylic adhesives with shedding capacity. Specifically, our design can mechanically shed a sacrificial layer in order to release the strong bond with minimal energy input. Our design utilizes multiple sacrificial layers which enable repeated use. This approach provides high force density (ranging from 10 to 30), low power consumption, and multi-surface gripping capacity.

We acknowledge that leaving a layer on the surface may be a drawback in some cases; however, there are many cases where this is not a concern. Some examples include robots that may need to manipulate debris, handle boxes, or perch on temporary structures.

We begin our paper by describing our core functional requirements for mobile manipulators. We then describe our overall sacrificial-adhesion approach. Two methods of operation are described: pump-based and pre-wetted. A specific UV sensitive acrylic adhesive is characterized both temporally, and over a range of materials. Finally, this work culminates with case study experiments using an industrial manipulator. These results demonstrate the load capacity, simplicity, and effectiveness of our approach.

II. FUNCTIONAL REQUIREMENTS

For mobile robotic gripping applications, weight, energy consumption, and versatility are important considerations. In the following list, we outline functional requirements for a broadly applicable gripper designed for mobile robots.

1) **Holding force to weight ratio greater than 10:1.** The ability to bear large loads relative to the gripper weight is crucial for mobile systems. A 10:1 ratio between holding force and gripper means that the overall weight contribution from the device is small.
2) **Controllable gripping.** The ability to control attachment and release enables broad usage. While centralized control is slower than reflexive behaviors, it offers greater robustness and versatility in operation.
3) **Low power consumption when initiating, holding and releasing grasp.** Low power usage is essential for mobile applications which must carry their own energy supply. Therefore power to initiate, hold and release the grasp should be minimized.
4) **Relative invariance to materials and geometry.** Mobile robots encounter a wide range of materials and surface properties while operating in different environments. Therefore, the ability to handle a broad range of materials is very important.
5) **Capable of repeated use.** Many applications such as perching and package handling require multiple grasp-release cycles. Therefore, grippers for mobile systems must be designed for several repeated uses.

Our review of literature did not identify a grasp framework that addresses these requirements. Therefore we have explored a new approach that leverages the strength of engineered adhesives, controllability through light sensitivity, and multiple uses via sacrificial layers. We refer to this methodology as “tunable adhesion with disposable elements.” Our specific manifestation utilizes a UV cured acrylic adhesive with disposable plastic layers. As we show in the following sections this design meets the aforementioned functional requirements, and therefore holds great promise for a range of mobile systems.

III. TUNABLE ADHESION WITH DISPOSABLE ELEMENTS

We begin this section by reviewing and evaluating options for the chemical adhesive. Next we overview materials and release mechanisms for the sacrificial layers. We also present two methods for depositing the adhesive on the sacrificial layer, both of which we implement as separate variants of our design.

A. Adhesive Curing Mechanism

Available adhesives vary by composition and curing mechanism, which in turn have different performance characteristics. Examples include two-part epoxies, cyanoacrylates, anaerobic adhesives, and photoinitiated polymerization.

Two-part room temperature adhesives are cured through a chemical reaction between a resin and a hardener. This method of curing is used with various chemical compositions, namely epoxies and polyurethane adhesives [21]. At room temperature, these adhesives exhibit high bond strength after the two components are mixed and cured [21]. However, readily available two-part adhesives are generally designed to have a long pot life at room temperature [22]–[24]. A prolonged cure time reduces the applicability to robotic gripping. Additionally, multi-part adhesives require the distinct components to be stored completely separate from each other. This accommodation can complicate storage design and result in an overall heavier prototype.

One-part adhesives demonstrate capabilities that are more suited to a compact, robotic gripper. Cyanoacrylates react rapidly to the presence of moisture, whether that be in the air or on the substrate. The reaction is fast and requires very little moisture, thus the glue starts curing after exposure to air [25]. Although a rapid cure time is ideal in practical applications, the instability of the adhesive in air may require additional design constraints. A heat-cured adhesive on the other hand is stable at room temperature, but will require the addition of a heat source, which would substantially increase power consumption.

Photoinitiated acrylic adhesives are composed of a photoinitiator and acrylate monomers. As ultraviolet radiation contacts the adhesive, the photoinitiator absorbs the radiation and releases free radicals, which initiates polymerization of

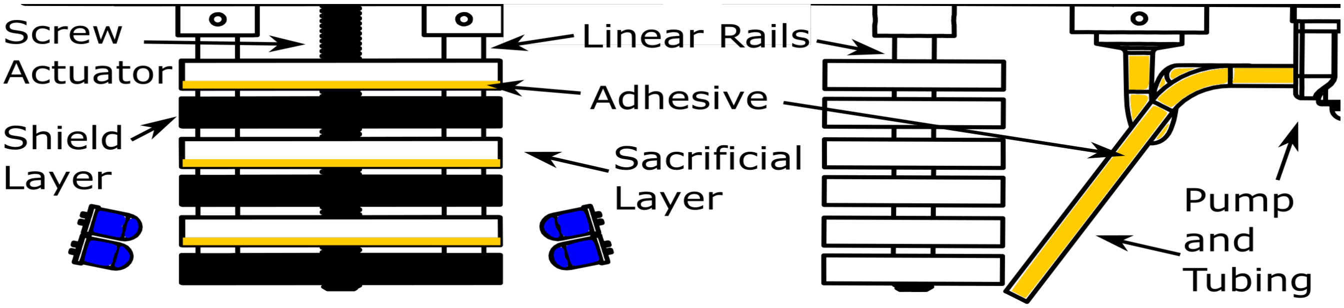

Fig. 2. Schematic of screw actuator, front view of pre-wetted design (Left), and side view of pump-based design (Right).

the monomers [26]. This method of curing shares the same advantages of a heat-curing system in terms of controllability, but we favor the photoinitiated adhesive due to the ability to cure with relatively low powered LEDs. It is noted that UV light is typically a safety concern, and this would need to be mitigated in design or application process.

Ultimately we chose to use a one-part UV-cured acrylic adhesive. One-part light-curing adhesives offer the attributes of single chambers, low power for initiation, rapid curing and relative environmental stability.

B. *Sacrificial Layer*

Based on our choice of the UV-curing adhesive, we desire a transparent layer material for simple transmission of UV light. Additionally the layer and its release mechanism should be strong and lightweight to meet the prior functional requirements. Since the sacrificial layers limit the number of consecutive uses, we desire a mechanism that can be easily reloaded.

We narrow down our selection to glass and clear plastics. Between these two categories, we favor plastics due to the brittleness of glass and a typically higher tensile strength. Ultimately we choose clear cast acrylic based on its strength, weight, and transparency.

We consider two options for release. The first method is to use a thin acrylic plate actuated by a screw and back-lit with UV LEDs. Multiple acrylic plates may be stored on the screw and moved up as old layers are removed. The screw may be reversed to reload new plates once the gripper is empty. Since the acrylic plates are transparent, LEDs may be mounted behind or to the side on the plates for curing.

An alternative method would be to use only the adhesive as the sacrificial layer. In this case, the acrylic plate would be a permanent component of the device and a cleaving action could be used to separate from the adhered surface. A similar design has been demonstrated for releasing a magnetic foot from a metal surface [27]. Using only the adhesive as a sacrificial layer is advantageous for simplicity of the layer; however, there are two drawbacks to this design. The first is the need for a high force to induce adhesive failure, which may require a heavy gear train. Additionally, there may be some adhesive left on the acrylic after every adhesion. This could gradually reduce UV transmissivity. Furthermore, the adhered surface may fail before the adhesive, which could render the gripper immediately useless.

We chose the screw actuated approach in order to maximize reliability and simplicity. The design meets the criteria outlined previously and can always separate from the sacrificial layer, even in the case that the adhered surface fails before the adhesive.

C. *Adhesive Deposition*

Our framework requires a method for depositing the adhesive onto the sacrificial layer. In this work we consider two means of adhesive deposition. The first design uses a pump to apply the adhesive from an on-board reservoir onto the target surface. The second implementation pre-wets the sacrificial layers with the adhesive prior to loading the gripper. Both variants, as pictured in Fig. 2, have advantages and drawbacks, and their use depends on the desired operation.

The primary benefit of the pump-based deposition is that the adhesive is kept contained and protected from ambient radiation until it is needed. The drawbacks to this method are the added weight of the pump and the time required to pump. The adhesive used in our design has a relatively high viscosity, 15-26 Pa·s, making it difficult to pump quickly. However, pumping time can be reduced through pump/chamber design as well as operation considerations.

Pre-wetted sacrificial layers can eliminate the weight, complexity, and time lag associated with pumping. However, such methods are more susceptible to UV radiation from the LEDs and the environment. Therefore, additional shielding layers are required.

IV. SYSTEM CHARACTERIZATION

We require a model for the adhesive behavior in order to use it as part of a controlled system. Specifically, we would like to predict holding force based on cure time. This information can be used to estimate maximum force as well as necessary cure duration. A relation between the strength of our gripper and exposure time to UV light is constructed empirically. Additionally we investigate the changes in strength due to varying surface materials. Finally we conduct analysis of the acrylic threads to determine the failure strength of the device itself.

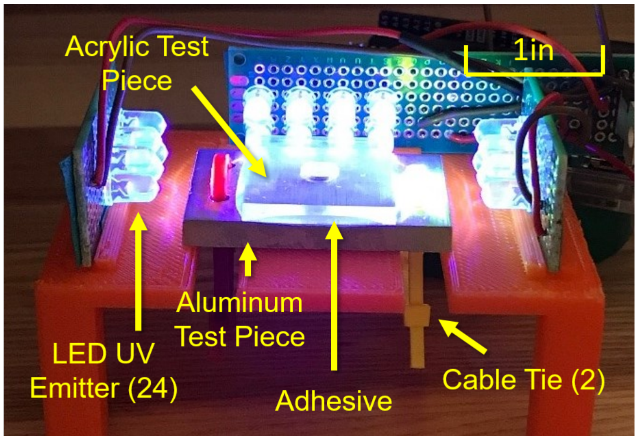

Fig. 3. Ultraviolet curing process for testing

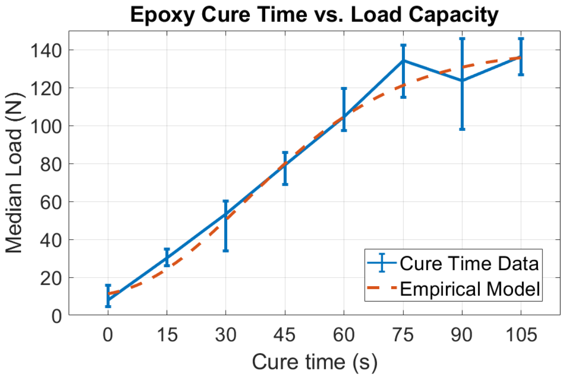

Fig. 4. Graphical depiction of cure time load test data (median)

A. *Adhesive Cure Dynamics*

To test the strength of the adhesive against different criteria, we built a test rig to apply a variable tensile load to the cured adhesive. We deposited uncured Loctite AA352 between a 29x25x3mm acrylic plate and a 29x44x3mm test material before initiating the cure process on a test bench pictured in Fig. 3.

The UV curing station is composed of 20 LED UV emitters (VAOL-5EUV8T4), a control circuit, and a power supply. We adjusted the power supply to ensure that each LED was drawing approximately 20mA of current at 3.3V per its specifications [28].

We tested the strength of the adhesive over different cure times and materials. The cure time tests were taken in 15 second increments between 0-105 seconds, inclusive. For the temporal tests, we used aluminum as the test material, since it is readily available and widely used in various applications [29]. The materials tests comprised of curing the adhesive between the same acrylic plate and six new materials to replace the aluminum: cardboard, acrylic, copolyester plastic (3D printer filament), steel, plywood and nylon.

Fig. 4 summarizes the findings from the cure time tests. We include error bars to depict the range in the data points. Additionally, we observed that all failures in the adhesive were between the acrylic piece and the cured adhesive.

The load capacity of the adhesive follows a positive trend until it plateaus at approximately 130 N after 75s of LED UV activation. We assume that this corresponds to the full cure of the adhesive. Even at shorter cure times, the adhesive has the potential to grip significantly more weight than the prototype itself (3.89 N). In practice, this means that the prototype can utilize shorter cure times when small loads are anticipated.

Prior literature has shown that photoinitiated polymerization can be modeled as an autoaccelerated reaction [30]. We fit our data to an equation from the literature shown below:

$$-\frac{dC}{dt} = k_{au}C^{m}(1-C)^{n} \tag{1}$$

In the above equation C is the remaining monomer and k_{au}, m, and n are constants, which we use as fitted parameters. For our model, we assume C starts near 1 and the monomer is completely spent by the end of the reaction. Furthermore, we assume that the holding force is proportional to the degree of cure, resulting in the following:

$$F = (1-C)\cdot F_{max} + F_0 \tag{2}$$

where F is the holding force, F_{max} is the holding force after full cure, and F_0 is the force applied by the uncured adhesive. Using a numerical fit, this yields the empirical model shown in Fig. 4. This may be used to predict a minimum cure time to increase operation rate.

B. *Material Dependence*

The results from the material test, presented in Fig. 5, show most of the materials fail at similar forces to the aluminum test piece. Additionally, we observe that the test pieces fail between the acrylic and adhesive for all except the copolyester plastic and cardboard, thus it can be assumed that the limiting factor for adhesive failure is the bond to the acrylic. This inspires future work to explore alternative materials for the gripper's adhesive plates.

The copolyester plastic and cardboard tests resulted in significantly reduced performance. The cardboard sample piece itself failed during the test, so the diminished performance can be attributed to material integrity. In the copolyester plastic tests, we observe that breakage occurs between the

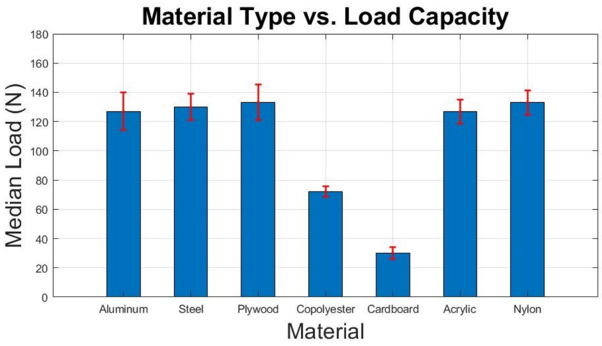

Fig. 5. Graphical depiction of materials load test data (median). The error bars show one standard deviation.

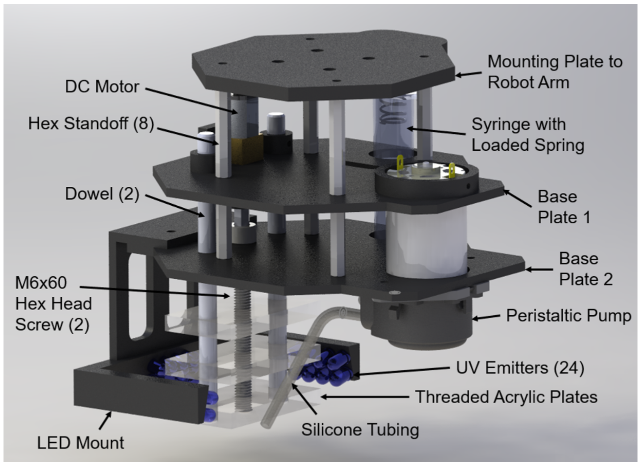

Fig. 6. Mechanical design of the gripper prototype: 3D rendering

cured adhesive and test material. We attribute this failure to lower compatibility between the material properties and adhesive, since adhesion to glassy polymers tends to be weak [31]. These results show that the performance of the gripper may be constrained by the material properties and structural integrity of the target object.

C. Thread Analysis

The strength of the screw-acrylic interface imposes an upper bound on grip performance. The acrylic plate is the weaker of the two materials, thus we focus on the shear stress on the internal threads. The following equation calculates the effective shear area of internal threads under load:

$$A_n = \pi n L_e D_{s,min}\left(\frac{1}{2n} + 0.57735(D_{s,min} - E_{n,max})\right) \quad (3)$$

in which n is the number of threads per inch, L_e is the thread engagement length, $D_{s,min}$ is the minimum major diameter of the external thread (screw), and $E_{n,max}$ is the maximum pitch diameter of the internal thread (acrylic) [32]. Using Eq. 3, as well as the internal/external dimensions of M6x1mm threads per ANSI/ASME B1.13M-2005 [33], the shear area of the internal threads calculates to 26.5mm^2. To obtain the pull out strength of the threaded interface, we use the average shear strength of cast acrylic (55.2 MPa [34]), which results in the maximum pull out force calculating to 1464N. This value serves as the theoretical maximum gripping force of the prototype, assuming the adhesive does not fail first.

V. PROTOTYPE DESIGN

In the following section, we detail the design and fabrication of a fully functional gripper prototype. Our design is intended to be modular and can be easily converted between pump-based methods and pre-wetted techniques.

A rendering of our design is shown in Fig. 6. We utilize FDM style plastic 3D printing for many of the parts. Acrylic plates are used for the sacrificial layers. Off the shelf electronics are used for the pump (INTLLAB 606015745013) and the LEDs (VAOL-5EUV8T4). The gripper functions using the following procedure:

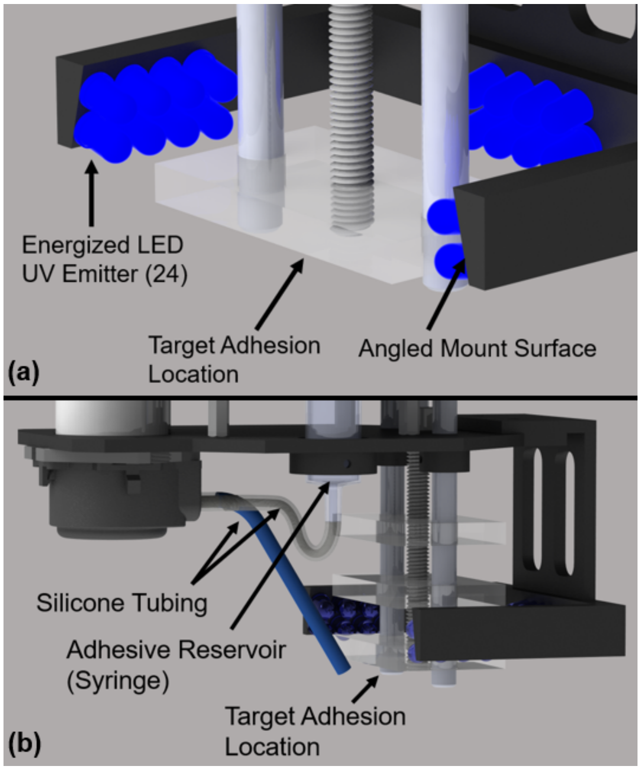

Fig. 7. (a) LED cure process. The angled mount surface directs the view angle of the LEDs to be pointed towards the target surface. (b) Peristaltic pump closeup. Silicone tubing runs from the adhesive reservoir (syringe) to the adhesive location.

1) **Dispensing the adhesive.** The pump dispenses adhesive from the syringe onto the adhesion surface through silicone tubing. The design uses a peristaltic pump, which keeps the adhesive separate from moving parts in case of premature curing. Fig. 7(b) presents a clear view of the components involved in this process. The pre-wetted deposition method would not require this step.
2) **Dispersing the fluid.** The lowermost acrylic plate is pushed onto the surface to spread the adhesive.
3) **Curing the adhesive.** The LED UV emitter array turns on for a set time to cure the adhesive. As seen in Fig. 7(b), the LEDs are angled slightly to orient them towards the adhesion surface.
4) **Holding.** During this step the gripper requires no input energy or signal.
5) **Release.** This process utilizes the screw mechanism to release the sacrificial layer. The assembly is clearly depicted in Fig. 8.

VI. FULL SYSTEM IMPLEMENTATION

Once the full prototype was fabricated we devised case-study experiments to demonstrate its performance using a conventional robot arm. These experiments are described below. The accompanying video illustrates these experiments.

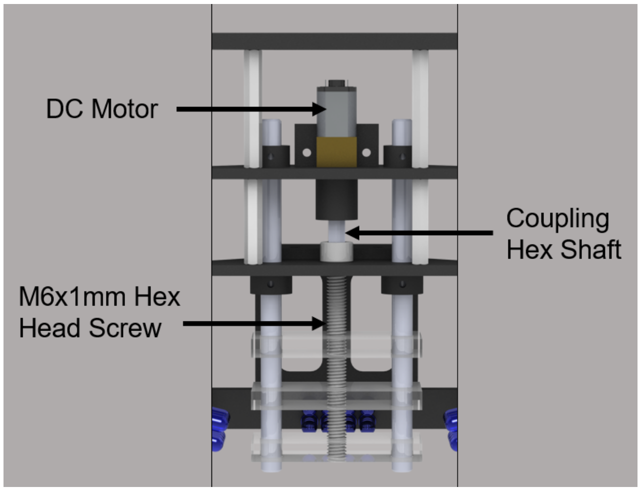

Fig. 8. Section view of the gripper. The motor and screw allow the acrylic plates to move either along the rails.

A. EPSON Robot Arm with Pump-Based Deposition

Following the completion of the prototype build, we tested the functionality of the device as an end effector on an EPSON C3 Manipulator [35]. Fig. 9 shows the full gripper system in the process of retrieving an object and placing it in a new location. The payload used in the retrieval process was a 50x100x150mm aluminum block with mass of 2.2kg. The cure time was 20 seconds.

The EPSON arm's specifications state that the maximum payload is roughly 3kg, and the target object used in testing approached this limit (total of 2.6kg with the gripper). Given the payload, the robot arm was operating at 85% capacity, while the gripper only reached approximately 15%. The longest sub-process of the gripping procedure was dispensing the adhesive (approximately 30 out of 60 seconds), which motivated us to explore the pre-wetted deposition method.

B. EPSON Arm with Pre-wetted Layers

To address the lengthy process time of the original gripper design, we modified the gripper design to incorporate the alternative adhesive deposition method of pre-wetting the acrylic plates. We removed the pump and syringe from the assembly and added opaque shielding layers to protect the adhesive from the LEDs. The shielding layers alone do not protect the adhesive from ambient radiation, but including an enclosure around the acrylic could solve this.

This new design significantly reduced the weight of the gripper to be 2.76 N. The overall procedure time also decreased to 30 seconds.

VII. CONCLUSION

This paper explored the use of cured adhesives and sacrificial layers for robotic gripping. Cured adhesives offer high force capacity with low input energy across a wide range of materials, making their use ideal for mobile robotics applications in unstructured environments.

We outlined the design of a robotic end effector which employs UV-curable adhesive as a gripping mechanism and sacrificial layers for release. The tensile strength of the curable adhesive was tested across cure time and surface material, and a functional prototype was built to demonstrate operation in practical application. Analysis was performed to quantify a theoretical model of the performance of the gripper based on cure time and surface material.

The experimental results of the load tests illustrate the adhesive layers' response time (15-75s depending on load), robustness to material type, and high holding force to weight ratio (10-30). Both the pump deposition method and pre-wetted deposition method were tested on a robot arm. The pre-wetted acrylic plates substantially reduced overall process time.

Current work is focusing on incorporating the gripper into mobile applications and designing a soft robotic gripper using this framework. A small-scale UAV has been selected as a platform that will be the first to use the gripper prototype to perch and hang from a surface. Replacing the hard acrylic plate with a soft, elastic material may allow for a wider range of use on different surface geometries. Recent advances in plant-based UV-cure resins [36] may also allow for an ecologically friendly implementation.

This work serves a model for future exploration into utilizing gripping mechanisms with curable adhesive, and introducing disposable elements into the grasping process.

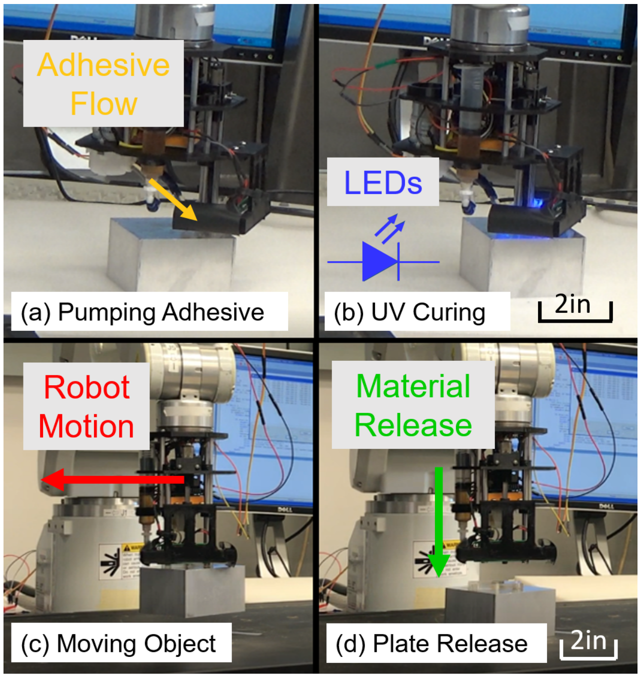

Fig. 9. Full gripper system in object retrieval process. a) The adhesive is dispersed onto the target surface. b) The LED UV emitter array is energized to cure the adhesive. c) The arm moves to new position. d) Acrylic plate releases along with the target object.

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