Slip in Bimanual Gripping of Deformable Objects with Gelsight Hybrid Adhesion

Rohan Punamiya

A thesis submitted in fulfillment of the

Undergraduate Research Option

Georgia Institute of Technology
2024

Reading Committee

Al Ferri, Chair

Ye Zhao

Yan Wang

Abstract

Robotic object manipulation has increased exponentially over the last couple of decades. Detection and prevention of slip of objects plays a vital role in secure object grasping and manipulation. Through the sensory feedback provided by their skin, humans possess the remarkable ability to readily perceive slip. To attain a level of skill comparable to humans, robots must be equipped with artificial tactile sensing integrated into their system. In this work, object manipulation is studied within the context of Agility Robotics' humanoid Digit robot. A custom mechanical bimanual gripper is designed to grip deformable objects with optical tactile Gelsight sensors equipped on each finger. The fabrication process is discussed in depth, along with the inverse kinematics model used to control gripper motion. After construction of the gripper, the problem of slip detection is decomposed into a classification problem by using the input from Gelsight sensors. The benefits and limitations of this novel design is discussed with future work on dynamic slip proposed.

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Introduction

Humans can construct representations of the world by detecting different stimuli from their environment through their sensory receptors and convert them into neural signals [1]. Although we are not able to precisely measure contact force, humans can get abundant information from tactile sensing, such as the objects' shape, texture, materials, and physical properties including mass, compliance, roughness, friction and thermal conductivity [2].

In the past few decades, the development of tactile sensor technology has become the forefront of robotic research that aims to imitate this human sensation with the aim of refining the robots' performance in grasping, and in-hand manipulation [2]. Those tasks, however, are still challenges for robots. These standard force sensors do not obtain enough tactile information at a high enough resolution for robots to deduce object shape and mechanical properties. One of the biggest developments to work around this has been a visuotactile sensor called GelSight which measures high-resolution geometry, and which can be used to infer local force and shear [2]. The sensor uses a deformable elastomer piece as the medium of contact, and an embedded camera to capture the deformation of the elastomer surface. The high resolution 3D geometry of the contact surface can be reconstructed from the camera images. When the sensor surface is painted with small black markers, the motion of the markers provides information about both normal force and shear force [2]. With the help of GelSight, a robot can easily capture the detailed shape and texture of the object being touched, which makes the touch-based object or material recognition much easier [2]. Research also shows that GelSight can also help a robot to sense multiple physical properties of the objects.

The high resolution signals provided by the sensors does come at a cost, with sensor design being constrained in terms of shape [3]. The very high resolution sensors based on GelSight have been constrained to flat or nearly flat designs, due to the difficulties of providing well controlled directional lighting with non-planar geometries [3]. This restriction limits the objects that can be held and detected by the GelSight to objects with flat surfaces.

The focus of this research is to determine the effectiveness of this GelSight sensor within the context of common dynamic locomotion tasks (throwing/catching common objects such as balls, moving carts, performing warehouse tasks). This builds on prior research into the mechanical design of the GelSight gripper, and its ability to firmly grip objects with a variety of mechanical properties with minimal slip. The aim is to create an optimal mechanical design that maximizes sensor resolution and reduces object perception error when detecting common objects in dynamic motion with a bipedal robot. Following the design phase, this study will show some experiment results on the robotic fingertip GelSight's performance on measuring geometry and force.

Tactile sensing is an important modality for robots, and one of the major challenges for robotic tactile sensing is to develop sensor hardware that can obtain adequate tactile information for multiple perception and manipulation tasks [2]. With the tactile information provided by the GelSight sensor, a robot will be able to perform much better in multiple tasks related to both perception and manipulation, resulting in more accurate human-robot interaction.

Literature Review

In the past few decades, researchers have developed many different tactile sensors for robots, and the core part of those tactile sensors is to detect the contact and contact force, or force distribution over the fingertip area [2]. With the force measurement from the fingertip tactile sensors, a robot is much less likely to break delicate objects. The contact detection and localization also refine the robots' performance in grasping, and in-hand manipulation [2]. For example, a successfully commercialized sensor is the tactile sensor array from Pressure Profile Systems, which measures the normal pressure distribution over the robot fingertip, with a spatial resolution of 5 mm [2]. The sensor has been applied to multiple commercialized robots, including the PR2 robot, and Barrett hands, and it successfully assisted common robotic tasks, such as contact detection and gripping force control [2]. Despite their commercial success, these grippers have only shown accuracy in limited environments, with very common objects. Detection of unknown objects with various mechanical properties is still the object of current research.

Among many robotic tasks that require assistance of tactile sensing, the most important task is to detect whether the robot has safely grasped an object. Slip, a common grasp failure, will occur when the gripping force is not large enough. The warning signals of slipping objects, such as the stretch of fingertip skin and the subtle vibration of a sliding object, can be easily perceived by humans [3]. For a long time, researchers have been trying to develop tactile sensors capable of detecting slip. Tactile sensors with this capability measure various tactile signals, including contact force, vibration, acceleration, and stretch of the sensor surface [3].

Detecting hardness is also particularly important. Many objects have distinct hardness which makes them easier to recognize, such as human or animal bodies, cushions, sponges, food, and fabrics. A robot would benefit from hardness detection to recognize those objects in daily tasks and choose proper contact force to avoid damage. Object hardness is generally measured by touch, but there are several challenges. It can be measured, for example, by comparing the contact pressure and indentation depth between the touch sensor and the contact object [4]. However, different object geometries give rise to different contact forces, correlation between the two is complicated, and measuring the object shape to sufficient precision is difficult for most touch sensors [4]. There have been several limited attempts to measure object hardness by tactile sensors, but they work only under strict conditions, like the precise control of contact movement and the single geometry or type of the objects.

Soft gripping can be categorized into three technologies: by actuation, by controlled stiffness, and by controlled adhesion [5]. Gripping by actuation relies on a squeezing force, which is the case in most bimanual mobile robots. Gripping by a controlled stiffness utilizes variable stiffness to conform to the object’s shape, then locking the registered shape. Gripping by controlled adhesion relies on shear adhesive forces at the interface between the gripper and object [5]. Within gripping by controlled adhesion, there are various controlled adhesive or “astrictive” technologies, such as suction, electrostatic adhesion, and dry adhesion [5]. Suction can provide high adhesive forces but is ineffective on porous materials and performs poorly on rough surfaces. It also adds weight and complexity, drawing energy from a mobile robot with limited battery power [5]. Electrostatic adhesion (electroadhesion) provides gentle contact and adhesion with surfaces while consuming very little power [5]. It can be used for handling fragile or deformable objects such as wafers or eggs. However, the adhesive pressure it provides is relatively low, limiting the weight of objects it can lift [5]. Gecko-inspired dry adhesives rely on Van der Waals forces to provide high values of shear adhesion with almost no internal normal forces. However, Van der Waals interactions only work when two surfaces are within very close proximity, and the performance is directly proportional to the amount of contact area between the adherend surface and the dry adhesive, making it perform poorly on non-smooth surfaces that result in a small real area of contact [5].

Those tasks, however, are still challenges for robots because these standard force sensors do not obtain enough tactile information at a high enough resolution for robots to deduce object shape and mechanical properties. One of the biggest developments to work around this has been a visuotactile sensor called GelSight which measures high-resolution geometry, and which can be used to infer local force and shear [2]. The sensor uses a deformable elastomer piece as the medium of contact, and an embedded camera to capture the deformation of the elastomer surface. The high resolution 3D geometry of the contact surface can be reconstructed from the camera images. When the sensor surface is painted with small black markers, the motion of the markers provides information about both normal force and shear force [2]. The vision-based design of the sensor also makes the hardware accessible and the installation much simpler, and the software for processing the raw data easier to develop by using the algorithms in computer vision [2]. With the help of GelSight, a robot can easily capture the detailed shape and texture of the object being touched, which makes the touch-based object or material recognition much easier [2]. Research also shows that GelSight can also help a robot to sense multiple physical properties of the objects.

The first GelSight prototype was developed in 2009 by Johnson and Adelson. Unlike other optically based approaches, GelSight works independently of the optical properties of the surface being touched. The ability to capture material-independent microgeometry is valuable in manufacturing and inspection, and GelSight technology has been commercialized by a company (GelSight Inc., Waltham, MA, USA) [2].

The high resolution signals provided by the sensors does come at a cost with sensor design being constrained in terms of shape [6]. The very high resolution sensors based on GelSight have been constrained to flat or nearly flat designs, due to the difficulties of providing well controlled directional lighting with non-planar geometries [6]. There have been several attempts at designing around this challenge by altering the shape of fingertips, however the inability to detect deformation in altered non-planar fingertips has reduced this to the subject of future study.

Beyond the design of the mechanical gripper, the integration with the bigger bipedal robot has been the subject of great study. By far, the most common approach to control is through the tracking of precomputed reference trajectories [7]. The trajectories may be determined via analogy, either with biological systems [7] or with simpler, passive, 1 mechanical-biped systems [8]. They can be generated by an oscillator, such as van der Pol's oscillator, or computed through optimization of various cost criteria, such as minimum expended control energy over a walking cycle [8]. Within the context of tracking, many different control methods have been explored, including continuous-time methods based on PID controllers [7], computed torque and sliding mode control [8], or essentially discrete-time methods, based on impulse control [8]. Other control methods have been investigated that do not rely on precomputed reference trajectories for the angular positions. These include controlling energy, angular momentum, and others [8]. In the course of the development of these results, it was observed that the zero dynamics of the biped was not invariant under the impact model. It was subsequently shown that its invariance could be recovered under high gain control [8].

Overall, the development of visuotactile sensors, in particular the GelSight sensor, have various applications within the field of bipedal robots. However, due to its design challenges, there is lots of ongoing research into optimizing this design and its integration into bipedal robot perception/sensation.

Methods and Materials

Gelsight Fabrication

With the goal of compact design while being able to form high-resolution 3D object reconstructions, the process described by Wang et. al. [9] was used to fabricate Gelsight sensors. All rigid parts (camera holder, mounting plate, sensor case, acrylic block, mirror) were either outsourced or 3D-printed using an Ultimaker S3 printer with standard Cura slicer settings and 20% material infill.

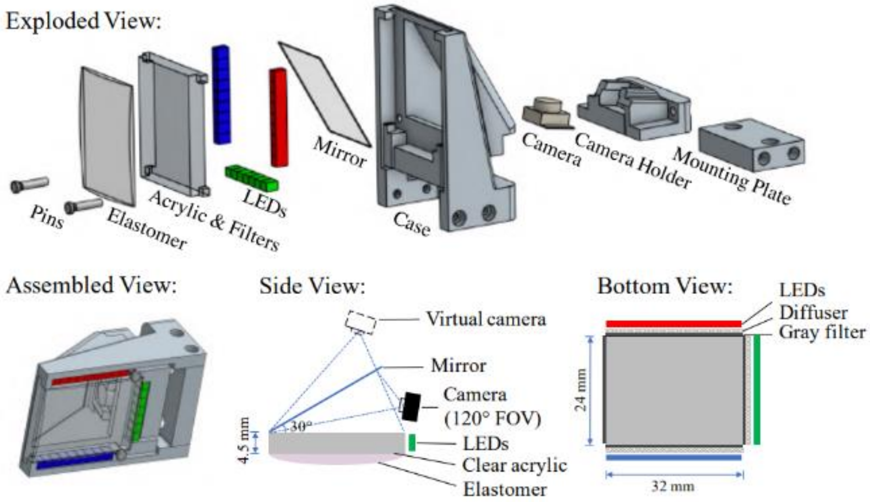


Figure 1: Sensor design, including the exploded view showing inner components, the assembled CAD model, and the schematics.

Elastomer

The silicone elastomer was fabricated using a Silicone RTV-2 P-565 Base and accompanying Activator [10]. The base and activator are thoroughly mixed together in a 10:1 ratio. This mixture is placed in a vacuum chamber until all air bubbles disappear. The mixture is taken out of the chamber and poured into a pre-designed 3D-printed mold with the necessary curvature. Optically, the curved gel provides more uniform illumination, as the curve makes the lights shoot from tilted angles to more direct angles as distance grows. This compensates for the decreased LED lights over distance. Mechanically, curved gel is more tolerant to flat and concave surfaces since it does not require the sensed surface to be perfectly aligned to the sensor surface. In our studies, the shape of curved gel is a part of an ellipsoid (a=b=60mm, c=100mm). After 24 hours, this elastomer can be removed from the mold and trimmed/shaved to fit the acrylic block dimensions. The elastomer is painted gray and then engraved with a grid of markers 2mm apart from each other, using a laser engraver. The backside (non-marked side) is painted black, allowing the markers to appear black against the gray marked side.

Figure 2: 3D-printed gel molds, with ellipsoid base.

Case and PCB

The 3D printed sensor case housing was also printed using the method outlined in Wang et. al., and exhibited all the necessary properties (Figure 3a). Upon testing, a yield strength of the case was found to be 26 MPa. While this satisfied the design requirement of a hard sensor, the PCB boards mounted on them (Figure 3b) were far thinner and much more fragile. Therefore, a better gripper design was designed and built.

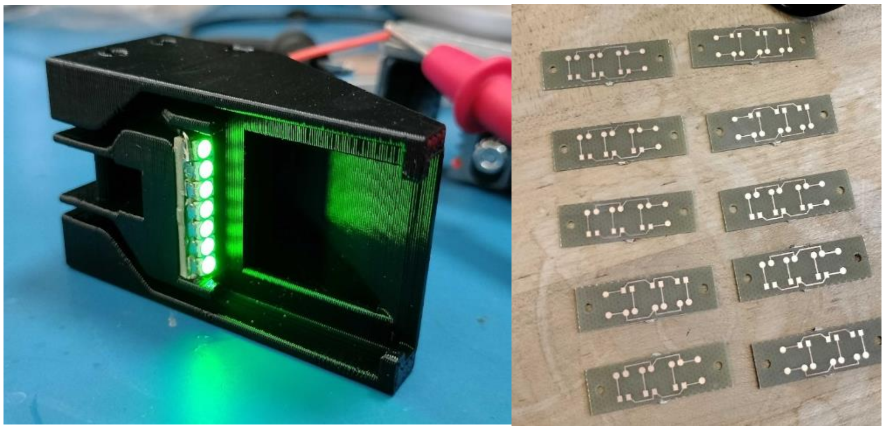


Figure 3: a) (left) Gelsight case with illuminated LED's. b) (right) Gelsight PCB boards.

Sensor Assembly

The silicone gel elastomer is attached to the acrylic block using Silpoxy adhesive. This subassembly is press-fit into the 3D-printed sensor case. The camera is press-fit into the 3D-printed camera holder. The camera holder is attached to the sensor case with M2 screws. Three lensless LED lights are soldered in arrays and taped into the sides of the sensor case to generate directional lights. The front-surface mirror is glued inside the case, which is tilted by 30 degrees.

Gripper Design

Gripper Mechanism

The following bimanual "lobster claw" gripper was designed with the constraints of weight, minimal components and actuators, space, and modularity.

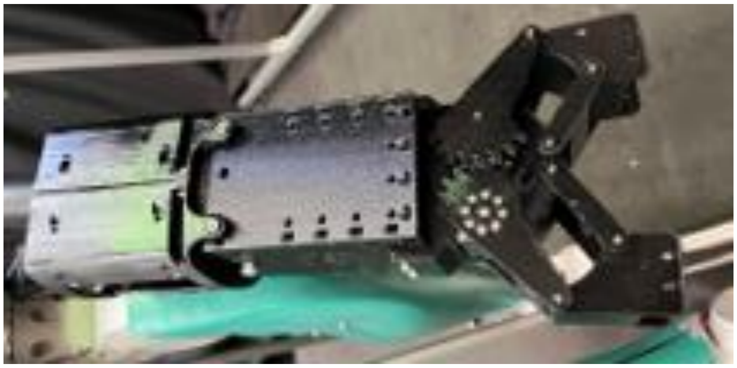


Figure 4: Bimanual "lobster claw" gripper installed onto Digit forearm.

From Agility Robotics' specifications [11], the Digit arm can support a total of 16 kg (35 lb) on its arm. To maximize the weight this arm could carry, an aim of a gripper weighing less than 1 kg was set. This constraint was in tandem with minimizing the number of components and actuators required to operate the gripper. Our team found that a 3D-printed gripper with one motor and a geared connection between both gripper fingers was the most robust design that adhered to those constraints best. The chosen motor was a Dynamixel XM-430-W350-T motor due to its high-performance control.

The space design constraint was not a high priority design constraint, as the gripper mounted around the forearm of Digit. As the gripper design continues to be optimized by testing different motors, components, and configurations, a sleeker gripper can be designed with fewer materials, perhaps even using topology optimization algorithms.

To increase the modularity of this gripper design, multiple mounting holes were designed into the gripper. This is for any necessary future work that might require mounting to the gripper (e.g. strong casing, additional sensors or actuators, etc).

Gripper V1

The first version of the gripper design was very similar to Wang et. al. in that it used a two-finger mechanism connected by a pulley to one Dynamixel servo motor (Figure 5). While this gripper design provided a good starting mechanism, the assembly process for this gripper was especially difficult, especially when attempting to route the pulley cables. Furthermore, the cables wore down after less than 100 operations.

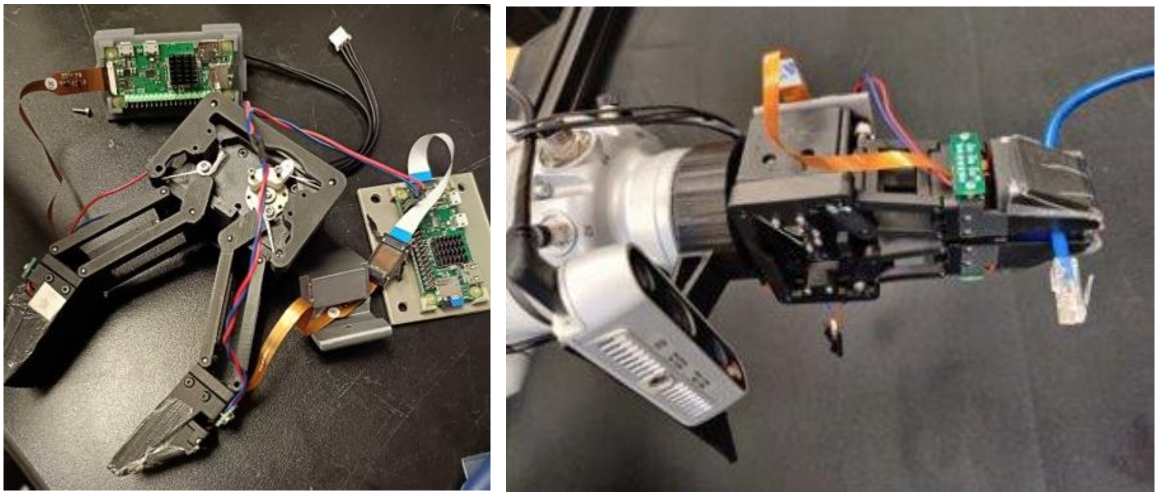


Figure 5: Initial gripper design, involving linkages connecting the Gelsight fingers to a cable pulley system, which is in turn hooked to a Dynamixel servo motor.

Gripper V2

The new gripper used a more robust gear-train system to actuate the squeezing of both fingers (Figure 6). By replacing the cabled system with 3D-printed mesh gears, the durability of the gripper theoretically increased to millions of use cycles. The forearm mount attachment in Figure 6 also made the gripper much easier to slide onto the Digit humanoid robot.

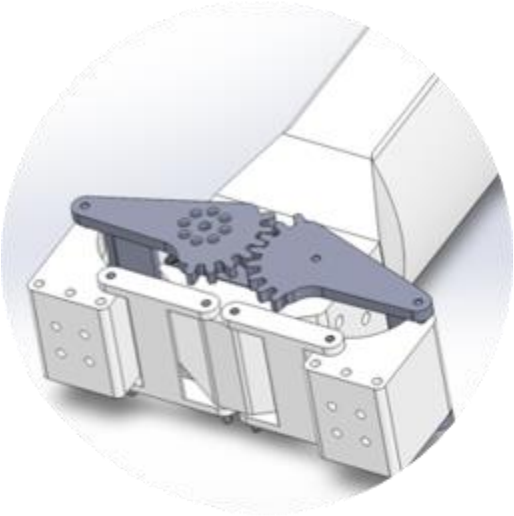


Figure 6: Gripper V2 design with geared finger mechanism, and forearm mount sleeve.

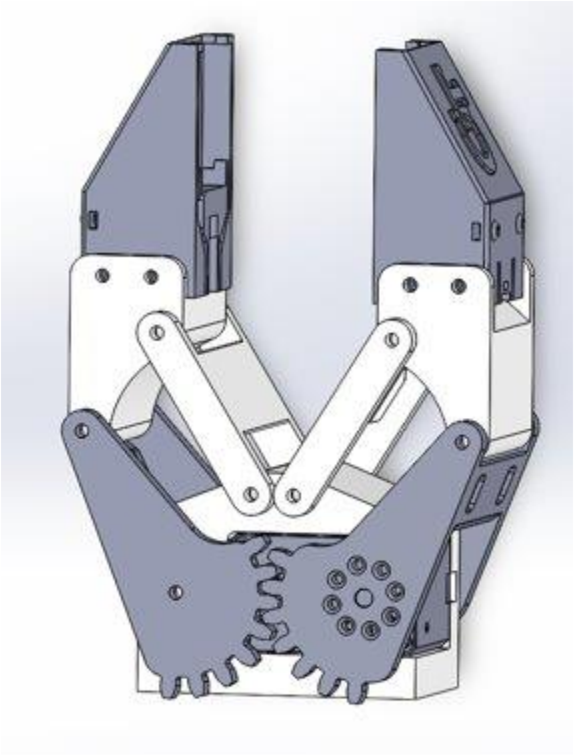


Figure 7: Front view of bimanual gear-based operation of gripper.

The full gripper design is illustrated in Figure 7. The main design changes made from Gripper V1 was the addition of a strong outer casing for the motor, and the geared mechanism mentioned above. This design was made completely modular by including the motor housing, creating space for sleeve attachment to Digit's forearm, and adding multiple mounting holes on the casing for any additional PCB's.

The biggest design flaw is the weight of the gripper. The current gripper weight of 326g is too much for the robot to handle when in its resting unpowered state. Hence a forearm extension must be designed to add forearm linkage strength.

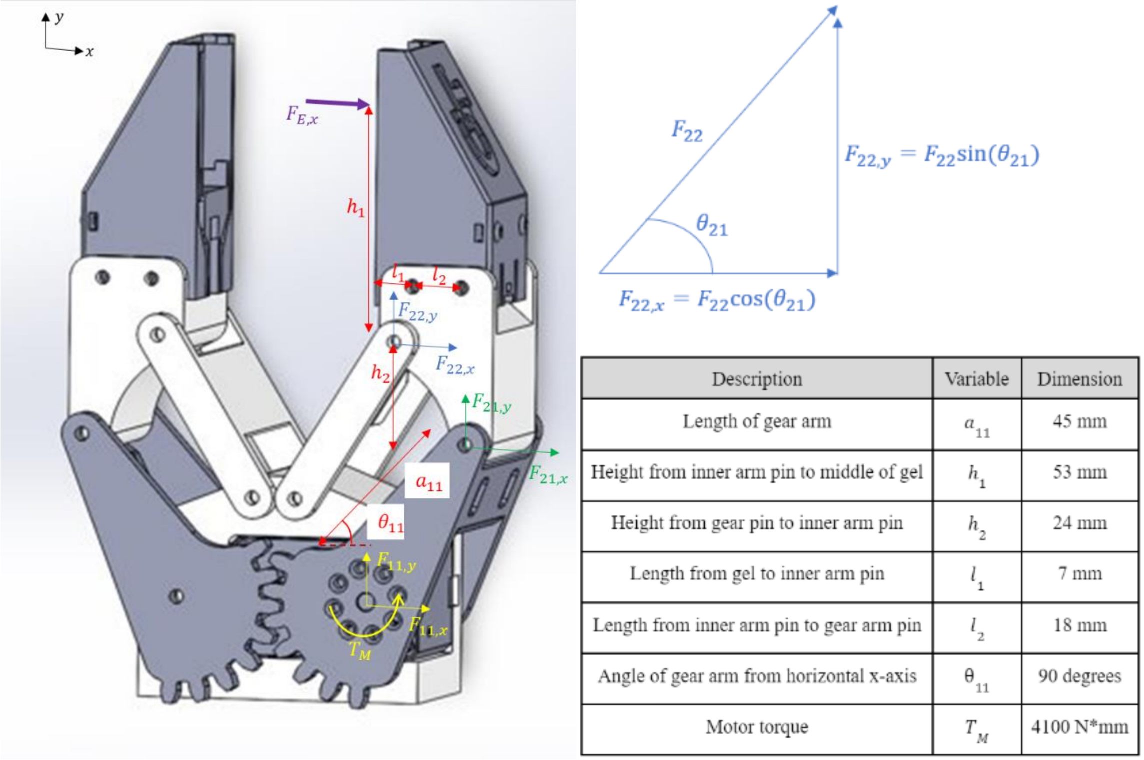
Forearm Extension

The aim of the forearm extension design is to create a stronger forearm linkage such that the Digit robot can hold the gripper weight rigid in an unpowered state. To create this, a linkage piece to Digit's elbow has been crafted, as shown in Figure 8.

Figure 8: Digit elbow modular linkage.

Upon completed fabrication of this forearm, the gripper easily slides onto Digit's arm.

Kinematics



Description	Variable	Dimension
Length of gear arm	a_{11}	45 mm
Height from inner arm pin to middle of gel	h_1	53 mm
Height from gear pin to inner arm pin	h_2	24 mm
Length from gel to inner arm pin	l_1	7 mm
Length from inner arm pin to gear arm pin	l_2	18 mm
Angle of gear arm from horizontal x-axis	θ_{11}	90 degrees
Motor torque	T_M	4100 N*mm

Figure 9: Gripper kinematics diagram.

$$F_E = \frac{T_m}{Q},\ Q = a_{11}\cos\theta_{11}\sin\theta_{12}\frac{h_1+h_2}{l_2\sin\theta_{12}+h_2\cos\theta_{12}} + a_{11}\sin\theta_{11} - a_{11}\cos\theta_{11}\sin\theta_{11}\frac{h_1+h_2}{l_2\sin\theta_{11}+h_2\cos\theta_{11}}$$

Equation 1: Gripper force inverse kinematics equation.

Using Figure 9 and Equation 1, the maximum force vector for the selected Dynamixel motor is 91N. With a maximum coefficient of friction of 0.45 [14], this implies a maximum theoretical frictional force of 41N, implying the gripper can theoretically carry an object of up to 4kg before slippage.

Extracting Force Data

The Lucas-Kanade method provided by the gsrobotics library from Gelsight [12] were utilized to track gel marker positions using the Raspberry Pi mini camera. Implementing those algorithms produced the results in Figure 10.

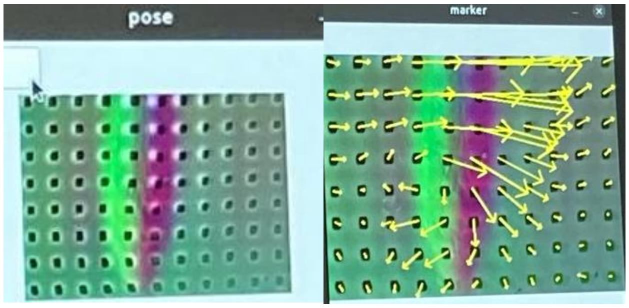


Figure 10: (left) Camera image of gripper pose. (right) Camera image with marker trackers indicating marker displacement from base untouched position.

This specific instance is an example of a finger pushing against the gel of the gripper. The camera detects the position and calculates the displacement of each marker from its original untouched state. This vector data is processed using equations outlined in [9] to obtain force vector data. For this instance, it can be deduced that the finger is gently rubbing the Gelsight sensor to the right side.

This optical flow method estimates the displacement of markers by examining the changes in pixel intensity from the known intensity gradients of the image in that neighborhood. The displacement of markers was directly correlated with the force applied to the sensor in Figure 11 by applying a best fit curve to the neo-Hookean curve presented. [13]

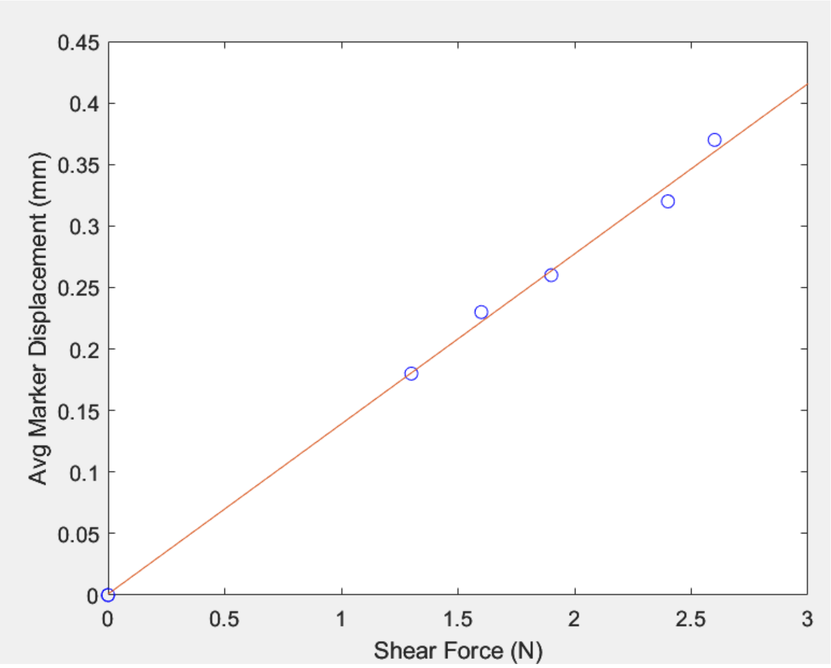


Figure 11: Correlation between average marker displacement of Gelsight sensors and shear force measured from object.

Results

The final gripper v2 design met all design constraints well. The gripper's weight being 326g implied it met the specification of being less than 1kg by a factor of safety of 2.32. Furthermore, after approximately 200 gripper attempts, there were no visible signs of stress or fatigue on any component of the system. The transition from the cable-driven mechanism to the gear-driven led to far fewer gripping failures. In comparison, with the cable-driven mechanism, on average there was at least one gripping failure occurring every 12 gripper cycles, often from the cable getting stuck in grooves in the gripper.

To test the robustness of the gripping mechanism against slip, a gradually increasing mass of solid non-deformable block was used, with the shear forces and shear displacements (based on average marker displacement) measured.

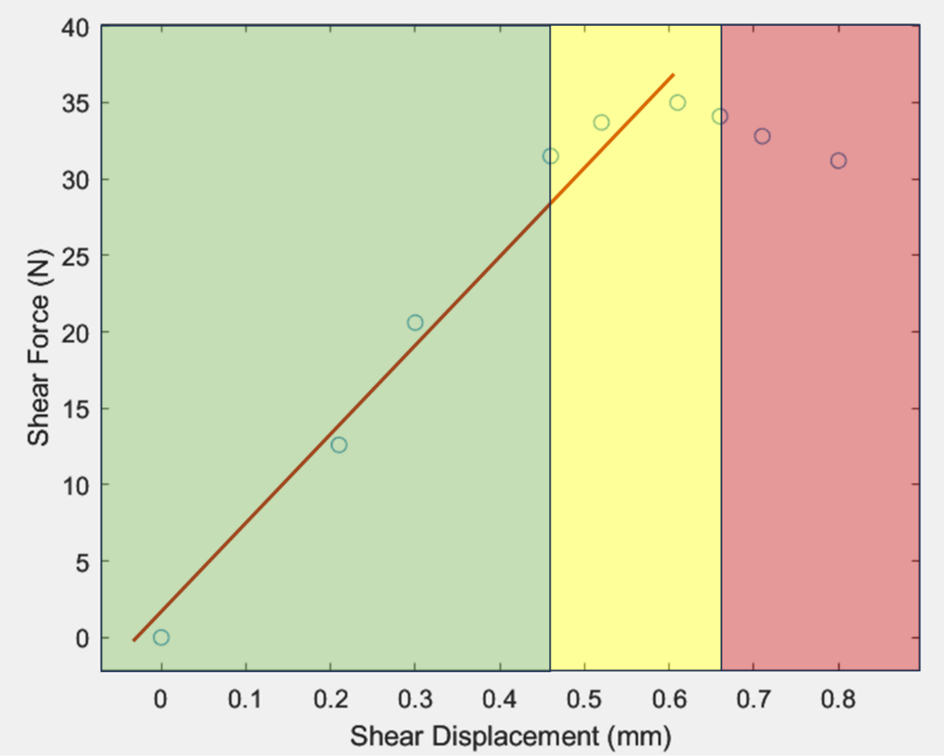


Figure 12: Correlation between object shear displacement and algorithmic detected shear force. Green zone indicates no slip, yellow zone indicates some slip, and red zone indicates significant slip.

Based on this model, the limits of the gripper mechanism can be set to 3kg objects. Beyond that, the gripper begins to exhibit slipping motion, as depicted by the lack of increase in shear force as shear displacement increases.

Discussion

To summarize, with the current bimanual gripper mechanical design with Gelsight sensors that utilize optimal-flow tracking, the Digit robot can securely grasp a static load of 3kg weight. The Gelsight sensors accurately reflect the external load profile of the grasped object, along with effective indication of slippage during shear loading. Measuring shear and slip during contact with objects is important for robot grasping, in that the warning of slip helps to prevent grasp failure.

The mechanical design of the gripper broadly met specifications. Minimal components were used, and lightweight PLA material was chosen to fabricate with in order to minimize the weight of the gripper. The design was completely modular, while also as sleek as possible to minimize its volume.

Obtaining a quantitative measurement of the force or torque with a tactile sensor using deformable polymer as the contact medium can be complicated due to the non-linearity and hysteresis response of the material. Sensor drift is a common issue with position estimation. However, surprisingly in our experiments, the average displacement of the elastomer markers was found to be consistent with minimal hysteresis. The gsrobotics library was very comprehensive in its ability to filter out any Gelsight marker sensor drift, resulting in accurate marker position measurements.

It must be noted, however, that our experiments involved far less than the 1000 presses which will cause permanent gel deformation [15]. More experiments to verify the sensors performance under different conditions must be conducted for a more robust conclusion.

Future Work

High Impact Design

One important consideration to make is that upon powering on, the Digit robot uses its stubbed hands to push itself into an upright position (Figure 13).

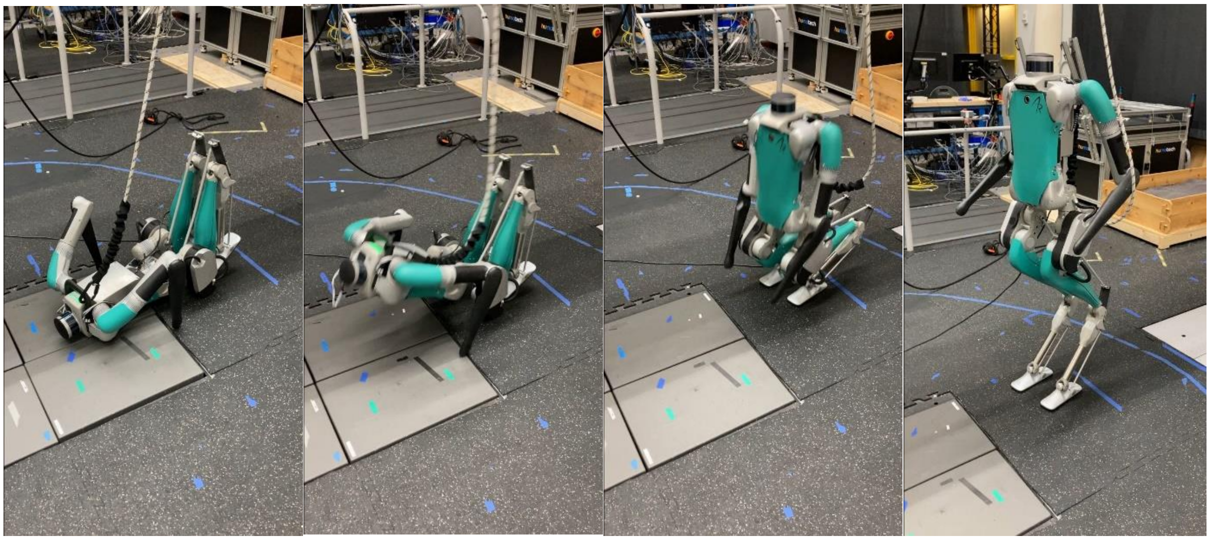


Figure 13: Digit getting up after power-on (left to right: Digit places hands on ground, pushes upward, leaps onto legs, and straightens up).

From this action, this 3D-printed PLA gripper design will not be able to withstand the compressive normal force from Digit pushing up against the ground. Thus, a carbon fiber gripper “knuckle” casing is being designed and will be mounted at the front of the gripper to withstand this high force. Future fabrication work and testing must be conducted to ensure such a gripper can withstand the high compressive force.

A future study on the effects of dynamic slip on active gripping and accuracy is also posited. With such a study, the upper bound of weight will likely further be reduced, as dynamic translational or rotational motion of the hand will require a stronger grip on the object. Furthermore, such motion may result in great distortions in Gelsight marker detection, resulting in poor estimation of slip.

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