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Development of a Bendable and Extendable Soft Gripper Driven by Differential Worm Gear Mechanism

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***Abstract*— A gripper mechanism using flexible double-rack finger actuated using differential worm gear mechanism that can change its finger length according to the object being grasped was developed. Thermoplastic polyurethane (TPU) based fingers were soft, impact resistant, highly compliant, and were able to conform to the contour of the objects when grasping. The fingers can extend, contract and bend in 2D space when driven by the differential worm gear mechanism. A normal worm and an inner worm gear was used to actuate the flexible double-rack fingers. The relative motions between the two worm gears resulted in different motions of the finger. Multiple fingered configuration of the gripper can be driven from the same mechanism actuated using two actuators. A mathematical model was developed to describe the kinematics of the finger for positioning experiments. Experiments were also conducted to measure the fingertip force for different lengths of the finger. Grasping experiments of two and three-finger gripper were performed to test the grasping performance of the gripper for objects of different size, shape and weight. The gripper successfully grasped objects of different sizes by adjusting the finger length and conforming to the shape of the objects.**

I. INTRODUCTION

Robotic grippers are commonly and extensively studied as end-effector manipulator for robotic arms. Traditional robotic gripper are designed to grasp a small range of products. This is not a problem when a robot is always handling the objects of similar size but causes a problem when grasping objects of large range of sizes. This has led to the development of multi-functional dexterous robot hands that are inspired by the human hand [1], [2]. However, despite being able to replicate human like motions and grasps, these hands have typically used rigid actuators. Soft grippers with dexterous grasping performance have been developed based on different actuation techniques such as soft pneumatic actuators [3], [4], [5], granular jamming [6], [7], cable-driven mechanisms[8], dielectric elastomer actuators (DEAs) [9], [10], and shape memory alloy(SMA) actuators [11], [12]. Most of the robotic grippers are pneumatically driven which makes the system bulky. Further, these grippers have a tedious manufacturing process which involves mold making and casting. Also some of these grippers are not suitable for grasping sharp objects and lack the ability to adjust the length of fingers to grasp objects of different sizes. There are also compliant gripper mechanisms [13], [14], [15] that rely on material deformation to achieve the necessary movement and adaptability, allowing the gripper to conform to the shape of the object being grasped. However, they are limited by force application, durability, and control complexity. Continuum robots whose manipulators being inspired from lightweight and flexible structures of animals, are capable of both extension and bending motions [16], [17], [18]. However, their extensions are limited by their design such as the elasticity of spring, origami and telescopic pipe length. A woodpecker-inspired robotic manipulator [19], [20] using flexible racks for bendable and extendable robot was developed but it was not specially designed as gripper and uses more actuators.

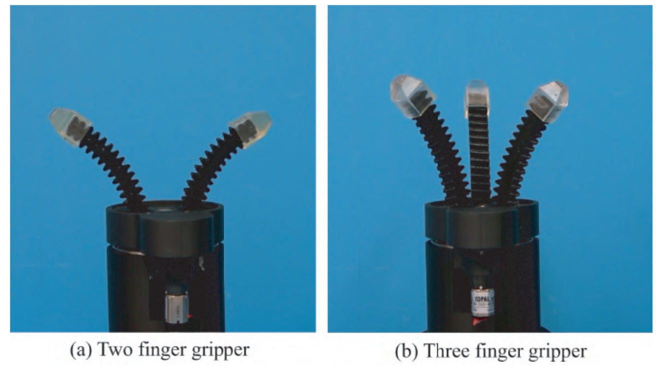

Fig. 1. Fabricated gripper with differential worm gear mechanism.

Extension and contraction are some ways for end effectors to utilize a workspace effectively. For example, frogs, chameleons, and anteaters are animals that are well-known for their extendable and bendable tongues. Especially in gripping application, when grasping a small object, the length of the finger can be smaller when compared to grasping a larger object. In this study we propose a robotic gripper mechanism that can extend, contract and bend the fingers in 2D space as shown in Fig 1. Soft and flexible double-sided 3D printed TPU rack gear that can slide between each other was used as the finger. The double sided racks was driven by a differential worm gear mechanism using two geared DC motors. The fingers were able to conform to the shape of the object being grasped thereby distributing the grasp forces over a larger area and reducing the chance of damage as localised forces are reduced. The larger contact area can also result in a more secure grasp. Multiple fingered configuration of the gripper can also be developed using the same mechanism as shown in Fig 1 driven by only two motors.

To summarize, this study has the following goals:

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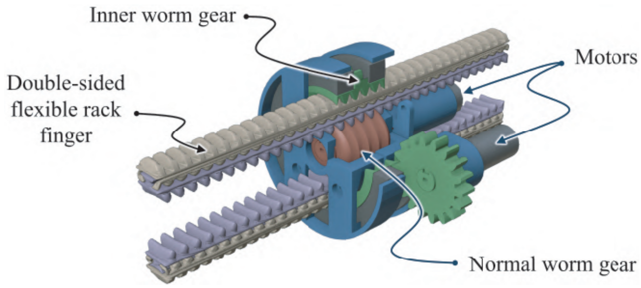

Fig. 2. Basic design of the soft gripper mechanism.

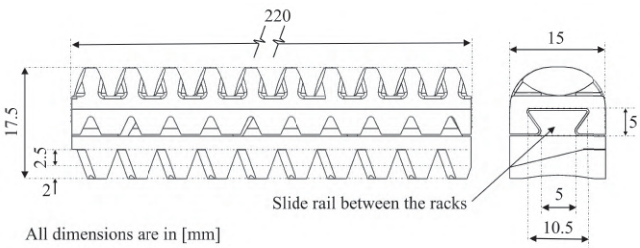

Fig. 3. Fabricated double-sided flexible rack finger and its design.

- Development of a gripper mechanism using flexible racks as fingers and driven using a differential worm gear mechanism. The incorporation of the differential worm gear mechanism facilitates diverse finger movements, including bending, extending, and contracting, all within a compact configuration.
- The adaptability of the developed mechanism to adjust the length of fingers when grasping objects of different sizes and shapes. The finger can also be stored within the robot arm until deployed.
- The suitability of the mechanism for driving multiple fingered grippers with just two motors.

II. Gripper Design

Fig. 2 shows the basic design of the gripper mechanism. The fingers of the gripper are fabricated from 3D printed TPU. The material choice justification is covered in later section. The fingers are designed in the form of double-sided rack gears that can slide freely between each other. The two rack gears are fixed on one end and free on the other. The fabricated finger and its design is shown in Fig. 3. The rack gear mating with the inner worm gear was crowned for smooth operation. The module of the gear racks and worm gears was 2mm and the overall length of the rack was 220mm. The finger bends when there is relative motion between the racks, resulting in sliding between the racks. The direction of bending depends on the rack length on either sides. The finger bends towards the direction of smaller rack length. The finger was driven by a differential worm gear mechanism. A normal worm mates with the bottom rack and an inner worm gear mates with the top rack. The relative motion between the normal worm gear and inner worm gear is used for driving the fingers.

The worm gears were fabricated from Polylactic acid

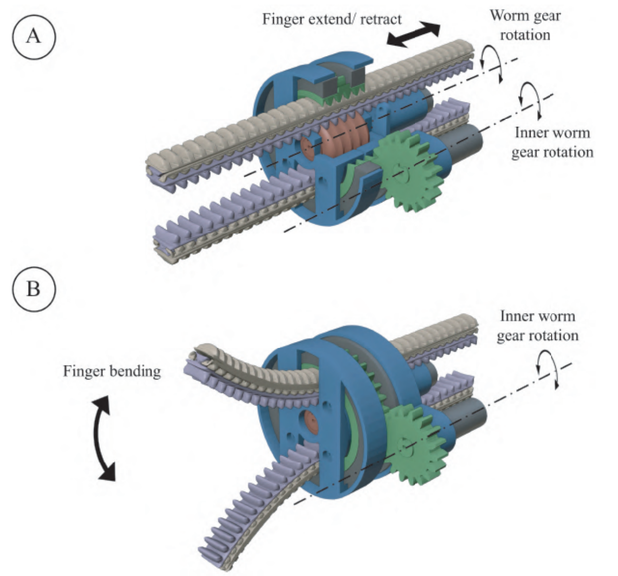

Fig. 4. Finger actuation mechanism. A) Finger extension and retraction. B) Finger bending.

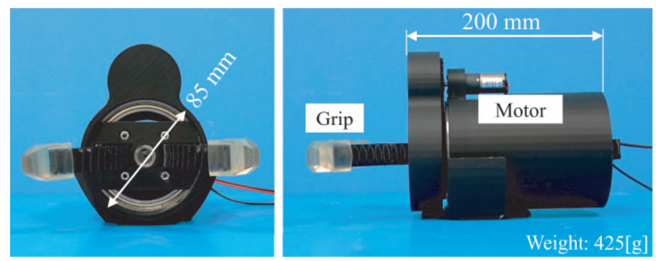

Fig. 5. Fabricated two-fingered gripper.

(PLA) and driven using a DC geared motor (NIDEC COPAL MG16B-300-AB-00). When both the worms rotate in the same direction with the same speed, the fingers extend or retract depending on the direction of rotation as shown in Fig. 4(A). When the inner worm rotates keeping the normal worm fixed, the finger bends inward or outward depending upon the rotation of inner worm gear as shown in Fig. 4(B). This bending action can be used for grasping the objects. When there is a relative motion between the normal and inner worm gears, a combination of extension, retraction and bending are observed. These finger configurations are resulting from the variation in the rack lengths of the finger. When the fingers are deployed its lengths cannot be altered easily by external means because of the non-backdrivability of the worm gears. The fabricated two-fingered gripper mechanism is shown in Fig. 5. The same mechanism can be extended for three-finger configuration as shown in Fig. 1. The two fingers are placed 180 degrees apart in the two-fingered configuration whereas three fingers are placed 120 degrees apart in three-fingered configuration of the gripper. A fingertip fabricated from Flexible 80A material was incorporated to enhance the gripping capability with objects due to its high surface friction properties. It is particularly helpful when objects are grasped by pinching about the fingertip.

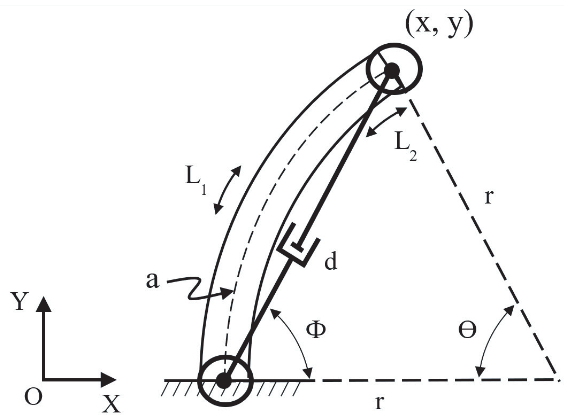

Fig. 6. Kinematic model of the finger.

III. Kinematic model

In order to control the position of the fingertip, it is vital that a kinematic analysis is performed to relate motor rotation to the magnitude and direction of finger bending. Since flexible rack gears can be considered as thin beams, constant curvature approximation [21] was applied. The lengths of the finger rack gears L_1 and L_2 can be changed by driving the worm gears. These rack lengths control the curvature (c) and arc-length (a) of the finger. The finger can be considered as a Revolute-Prismatic-Revolute pair as shown in the Fig. 6, and the final orientation of the finger can be derived from the curvature and arc-length. The rack lengths are converted to curvatures and arc arc-lengths as follows.

$$c = \left(\frac{L_2 - L_1}{L_2 + L_1}\right)\frac{2}{b}, \tag{1}$$

$$a = \frac{L_1 + L_2}{2}, \tag{2}$$

where b is the distance between the pitch line of one rack to the other. The sign of c determines if the finger is bending inward or outward. The motor rotation angle was derived by attaching an encoder to the motor. For every one rotation of the worm gear, the rack gear moves a pitch distance. Thereby the length of racks deployed can be determined from the motor rotation to evaluate the curvature and arc-length. The end position of the fingertip [x, y] can be calculated as follows.

$$d = \left|2r\sin\left(\frac{\theta}{2}\right)\right|, \tag{3}$$

$$r = 1/c, \tag{4}$$

$$\theta = ca, \tag{5}$$

$$x = d\cos(\phi), \tag{6}$$

$$y = d\sin(\phi), \tag{7}$$

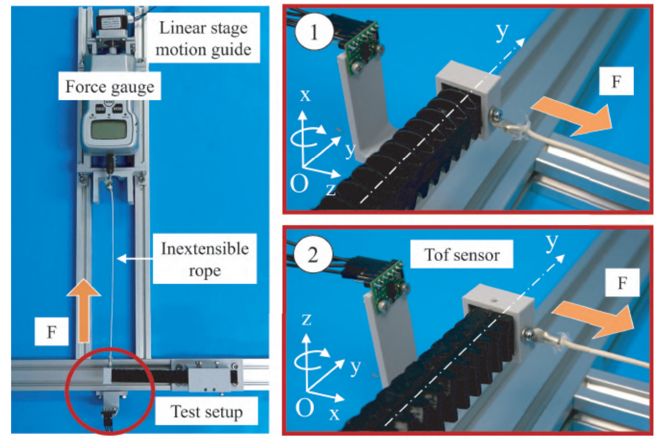

Fig. 7. Experimental setup for stiffness measurement. 1) Test setup for bending of the finger about X-axis. 2) Test setup for bending of the finger about Z-axis.

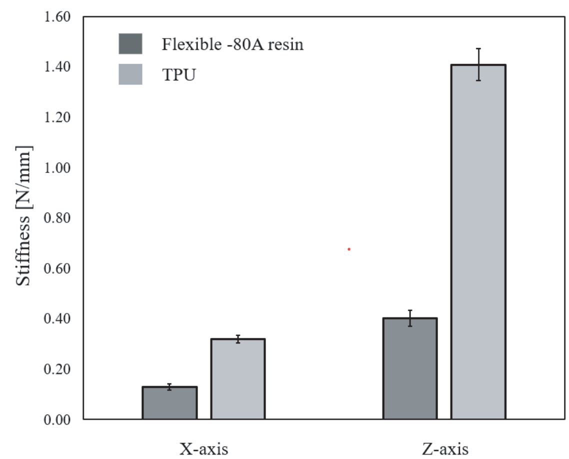

Fig. 8. Stiffness of TPU and Flexible 80A in X and Z-axis.

$$\phi = \frac{\pi - \theta}{2}. \tag{8}$$

From the above equations, it can be noticed that there is a singularity when the finger is straight, ie when $L_1 = L_2$. To avoid this singularity always a minor difference in the lengths of the racks is maintained. To obtain the inverse kinematics, for a given fingertip configuration [x,y], the values of L_1 and L_2 can be estimated numerically using the above equations which can be input to the system in terms of motor rotation.

IV. Experimets and results

Experiments were performed to evaluate the performance of the finger and the results are presented.

A. Finger stiffness

The finger must be flexible but at the same time, high stiffness of the finger is important to achieve high load carrying capacity of the gripper without buckling. There is a trade off between the finger's flexiblity and stiffness. Two different materials were tested for its suitability in gripper mechanism. Fingers fabricated from Flexible 80A

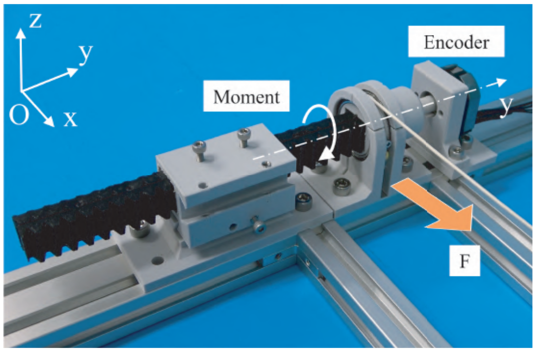

Fig. 9. Test setup for torsional stiffness measurement.

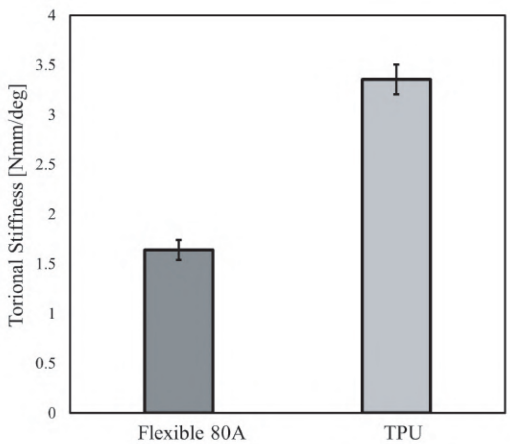

Fig. 10. Torsional stiffness of TPU and Flexible 80A.

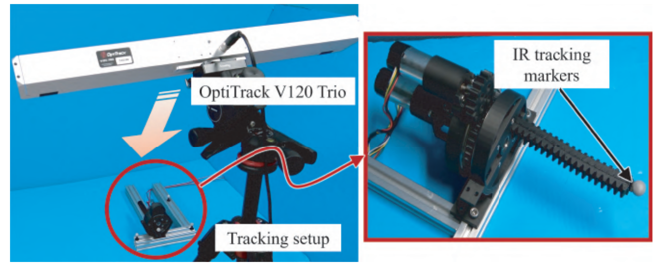

Fig. 11. Experimental setup for motion range estimation.

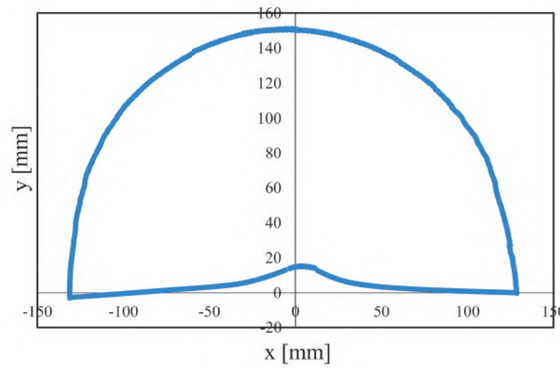

Fig. 12. Motion range of the finger.

using FormLabs Form 3 printer and 3D printed TPU based fingers were tested. Stiffness of the finger along various axes and its torsional stiffness were measured. The test setup for stiffness measurement is shown in Fig. 7. The length of finger under testing was arbitrary chosen at 50mm, where one end of the finger was fixed to the base and the other end was subjected to force application. The stiffness was measured when the displacment was applied to the end of the finger by a force gauge (FGPX-5, Nidec SHIMPO) using a linear stage motion guide actuator driven by a NEMA 17 (14HS17-0504S) stepper motor. The displacment of the finger was measured using a time-of-flight (VL6180X) sensor. The stiffness was defined as the inclines of the force-displacment curves obtained using the method of least-squares. Fig. 8 shows the measured siffness of Flexible 80A and TPU. The measurements were taken for five repeated trials and the error bar indicates the standard deviation for the five readings. It can be seen that the stiffness of TPU is about 3.5 times higher than Flexible 80A.

Fig. 9 shows the test setup for torsional stiffness measurement used in the experimental setup of Fig. 7. Torque was applied at the end of the finger and the angular rotation was measured using absolute encoder (490-AMT203-V). Torsional stiffness was defined as the inclines of the torque-angular displacement curves obtained using the method of least-squares. Fig. 10 shows the measured torsional siffnesses of Flexible 80A and TPU. The measurements were taken for five repeated trials and the error bar indicates the standard deviation for the five readings. It was found that torsional stiffness of TPU was twice that of Flexible 80A. Thus, TPU was chosen for fabricating the finger because of its high stiffness compared to Flexible 80A. In addition, other flexible materials with good flexibility and stiffness can also be candidates for finger fabrication.

B. Positioning experiment and motion range of the finger

The overall motion range of the finger was estimated by using the experimental setup shown in Fig. 11. The real-time positions of the fingers was estimated by tracing the infrared reflection markers (IR- Markers) attached to the fingertip. Positions of the tracking marker were measured by the motion-capture system (OptiTrack V120 Trio (120Hz), Natural Point Inc, Oregon, USA). The overall motion range of the finger tip obtained by driving the finger to its maximum and minimum limits is shown in Fig. 12. It can be seen that the finger has quite a large range of operation.

The positioning experiment of the fingertip was performed using the equations listed in the kinematic section and the real-time position of the fingertip was estimated using the experimental setup shown in Fig. 11. Fig. 13 shows the sequential motion of the finger along various setpoints actuated by the feedback obtained from the hall sensor based encoders of the motors. Fig. 13 also shows the positioning accuracy of the fingertip manipulated to different poisitons shown in the left side. The measurements were taken for ten repeated trials and the error bar indicates the standard deviation for the ten readings. It was observed that the

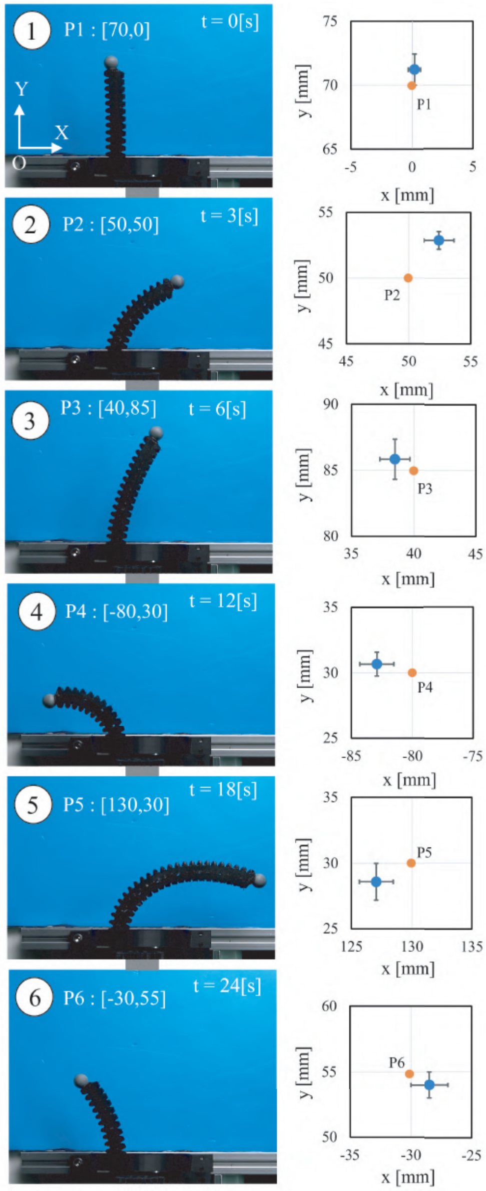

Fig. 13. Sequential motion of the finger along different setpoints.

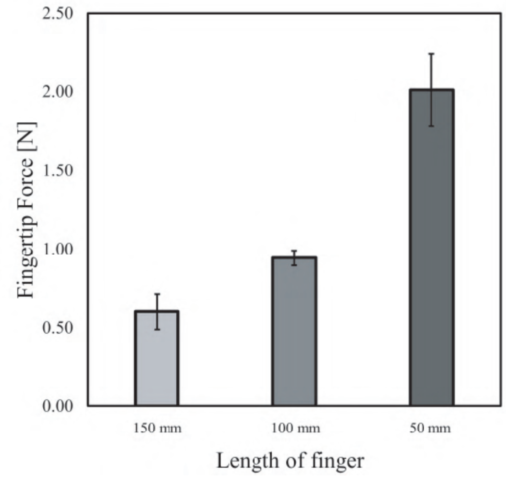

Fig. 14. Force at fingertip for various finger lengths.

Fig. 15. Grasping experiments of two and three-fingered gripper.

positioning accuracy was satisfactory with a maximum error of ± 4mm. The finger kinematics helps in understanding and predicting the configuration of the finger if its extended, retracted, bent inward or outward.

C. Fingertip force measurement

The same experimental setup shown in Fig. 7 was used for fingertip force measurement. The fingertip was prevented from displacement by attaching it to a force gauge. When the finger was made to bent to its highest degree, the force experienced by the fingertip was measured and recorded for different finger lengths of 50mm, 100mm and 150mm. Figure. 14 shows the experiment results and the error bars indicate the standard deviations of five readings. It can be seen that the finger with 50mm length applies a force of approximately 2.3N which is four times the force at the tip compared to 150mm finger length. This reduction in end tip force for a longer gripper is primarily due to increased leverage and torque demands. Hence, when grasping a small object, gripper mechanism with smaller finger length can grasp the object more effectively than a finger with longer length.

D. Grasping experiments

Fig. 15 shows an overview of the soft gripper with two and three-fingered configurations grasping various objects of different sizes and shapes whose details are listed in Table I. The experimental result shows that the gripper was able to grasp a wide variety of objects. It was observed that when grasping irregular shaped objects, the fingers changes its posture to adjust to the target shape, resulting in uniform stress distribution. Further, the gripper mechanism was able to extend or retract the finger length according to the size of the object being grasped. Two finger gripper was effective in grasping objects of uniform shapes and sizes. However, three finger gripper was effective in grasping irregular shaped objects.

TABLE I
DETAILS OF GRASPED OBJECTS

Objects grasped by two-fingered gripper

Sl No	Object	Dimension [mm] (Approximate)	Weight [g]
1	Screw driver	ϕ 15 × 175	100
2	Aluminium block (short side grasped)	75 × 75 × 20	50
3	Aluminium block (long side grasped)	75 × 75 × 20	50
4	Paper cup	ϕ 60 × 80	30
5	Plastic bottle	ϕ 75 × 160	150
6	Wet tissue box	ϕ 110 × 175	175

Objects grasped by three-fingered gripper

Sl No	Object	Dimension [mm] (Approximate)	Weight [g]
7	Egg	ϕ 45	50
8	Potato	ϕ 60	80
9	Half-sphere	ϕ 60 × 50	75
10	Rectangular block	100 × 50 × 30	100
11	Mini-tool box	100 × 75 × 60	200
12	Spool	ϕ 105 × 50	110

V. CONCLUSION

A novel soft gripper that can change the lengths of the fingers using a differential worm drive mechanism was developed. Two and three-fingered configuration of the gripper were fabricated using the single mechanism driven by two motors. The fingers were tested for linear and torsional stiffness and best suited material for the fingers was chosen. However, efforts are made to check for variety of materials for its suitability in the gripper mechanism. Currently, TPU which outperformed Flexible 80A was chosen to fabricate the fingers. The kinematic model of the finger was developed and tested for positional accuracy which was found to be satisfactory with maximum error of ± 4mm. The mechanism showcased its capability to change the length of the finger when grasping objects of different sizes and shapes. Since the gripper deforms according to the gripped objects, it can achieve the holding force through the effects of both friction and geometrical interlocking. Finger tip force is a function of the gripper length and decreases with increasing finger length because of the demanding torque or moment conditions. Current prototype was able to deliver an approximate force of 2.3N at the finger tip for 50mm finger length which is four times the tip force exerted by a 150mm finger.

Gripper mechanism with different modules of rack and worm gears, and finger dimensions are to be tested for better performance against buckling. In the future, we will incorporate the gripper mechanism in a robotic arm and test for its dynamic real-world performance. The fingers can also be stored safely inside the robotic arm until deployed for specific applications.

VI. ACKNOWLEDGEMENT

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