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Improving Robotic Manipulation Without Sacrificing Grasping Efficiency: A Multi-Modal, Adaptive Gripper With Reconfigurable Finger Bases

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ABSTRACT This work proposes a framework that improves the dexterous manipulation capabilities of two fingered grippers by: i) optimizing the finger link dimensions and the interfinger distance for a given object and ii) analyzing the effect of finger symmetry and the distance between the finger base frames on their manipulation workspaces. The results of the workspace analysis motivate the development of a multi-modal, adaptive robotic gripper. In particular, the finger link lengths optimization problem is solved by a parallel multi-start search algorithm. The optimal link lengths are then used for the workspace analysis. The results of the analysis demonstrate that different inter-finger distances lead to completely different workspace shapes and that the ratio defined by the area of the optimized workspace (nominator) and the union of all workspaces (denominator), is always significantly less than 1. This means that the area of the union of all workspaces is always larger than the area of the ''optimized'' workspace. Based on these results the proposed robotic gripper is equipped with reconfigurable finger bases that vary the inter-finger distance as well as with selectively lockable robotic finger joints, offering an increased dexterous manipulation performance without sacrificing grasping efficiency. The device is considered multi-modal as it can be used both as a parallel jaw gripper and as an adaptive robotic gripper.

INDEX TERMS Design optimization, dexterous manipulation, robot grasping, robotic grippers.

I. INTRODUCTION

Robotic hands and grippers are employed as end-effectors of robotic platforms to facilitate their interaction with the environments surrounding them (e.g., grasp an object, push buttons, open a door). The versatility and ability of the grippers to manipulate a wide range of objects across many use cases and scenarios from service tasks [1] to industrial tasks [2], as well as their effectiveness in completing these tasks can be used as an indicator of their dexterity [3]. Traditionally, such complex tasks are executed by employing fully actuated, expensive, rigid robotic hands that require advanced sensing elements [4], [5]. However, the sophisticated control laws and schemes required by these hands to operate efficiently complicate their operation. The relatively new class of adaptive (underactuated and compliant) robotic grippers and hands aims to address these shortcomings, offering task execution robustness with simplified control. These devices demonstrate excellent performance in the execution of robust grasping and dexterous manipulation tasks [6], [7], without requiring sophisticated learning and control schemes [8]. The superior grasping performance of adaptive hands is typically attributed to the introduction of structural compliance combined with underactuation that make control simpler and more intuitive [9]. These characteristics have led to a surge in the number of studies that focus on adaptive end-effectors. However, the structural compliance and underactuation compromise the pinch grasping capabilities of the gripper, introducing a post-contact parasitic reconfiguration of the gripper-object system that affects grasping stability [10].

The optimization of the gripper link lengths is vital for the minimization of the reconfiguration and the maximization of the grasping quality and stability achieved by such a robotic

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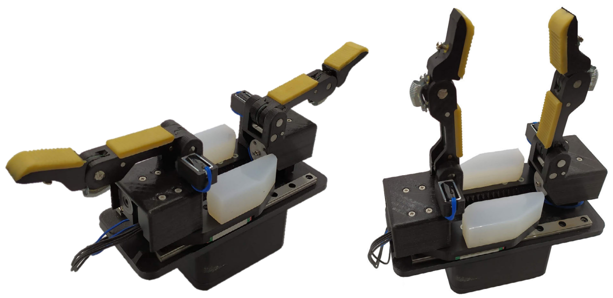


FIGURE 1. The proposed multi-modal gripper that is equipped with reconfigurable finger bases to improve dexterous manipulation without sacrificing grasping efficiency.

end-effector. Moreover, the distance between the finger base frames highly affects the grasping and manipulation capabilities of the gripper as well as the post-contact reconfiguration of the gripper-object system.

In this paper, we propose a framework that improves the dexterous manipulation capabilities of two fingered grippers by optimizing the finger link dimensions and analyzing the effect of finger symmetry and the distance between the finger base frames on their manipulation workspaces. The results of this analysis are used to design a new, improved, multi-modal robotic gripper that performs significantly better than other grippers in the execution of dexterous manipulation tasks without compromising grasping efficiency. To solve the optimization problem, we employed a parallel multi-start search algorithm. The optimal link lengths were used to investigate how the inter-finger distance, the design symmetry, and the object size affect the manipulation workspace. The results demonstrate that different inter-finger distances lead to completely different dexterous manipulation workspace shapes and volumes and that the area of the union of all workspaces is always larger than the area of any single "optimized" workspace. Motivated by these results, we designed a two fingered, multi-modal gripper with reconfigurable finger base frames and lockable joints. This ensures that the gripper can cover the union of workspaces rather than a single optimal workspace. The proposed gripper is considered multi-modal as it has a locking function implemented with solenoids that allows it to transition between an adaptive grasping configuration and a parallel-jaw gripper configuration as shown in Figure 1. The contributions of this research work are: i) an optimization scheme for improving the dexterous manipulation capabilities of robotic grippers and hands and ii) a novel, multi-modal gripper design with reconfigurable finger bases and lockable joints that exhibits improved manipulation capabilities without sacrificing grasping performance.

II. RELATED WORK

A number of studies have focused on optimizing the design parameters of underactuated and passively adaptive robotic hands so as to achieve increased performance over a large set of objects and grasping tasks [11]–[13]. The design characteristics of individual fingers determine their ability to interact with other fingers and the environment as well as to robustly grasp and manipulate various objects. More specifically, the two most important parameters that contribute to the effectiveness of a robotic gripper or hand are the link dimensions and the palm width (distance between the finger bases) [14]–[17]. Both of these parameters directly affect the range of objects that can be grasped and manipulated (different sizes and shapes). Design optimization of underactuated robotic gripper parameters has been employed in a number of studies to offer increased dexterity despite the small number of controllable degrees of freedom that is used in such devices. The main parameters that are optimized in these studies are the link dimensions of the fingers. Previous work has focused on the effect of gripper dimensions on contact force distribution [14]. Six of the seven design variables that were optimised using the teaching-learning based optimisation algorithm in this study were the dimensions of the gripper. Dong *et al* employed a genetic algorithm to find the ideal gripper dimensions as well as the most appropriate tendon routing solution, which would optimize the grasping performance of an underactuated robotic gripper [15]. Datta *et al* employed a multi-objective evolutionary algorithm to find the optimal link lengths as well as the joint angles of a robot gripper [16].

Once the optimal finger dimensions of a gripper have been determined, the ideal inter-finger distance needs to be calculated as it directly affects the functionality and dexterous manipulation performance of the system. In particular, the dexterity of a gripper or hand is mainly attributed to its fingers' ability to impart large object motions and forces during precision grasps, perturbing the object pose [18]. Studies have also proposed performance indices to quantify this interaction that leads to in-hand manipulation. You *et al* have quantified the ability of the fingers to interact with each other, using a performance index called "Interactivity of Fingers (IF)" and they employed this index so as to optimize the Saddle joint's position and orientation [19]. The relation between the manipulation workspace and the kinematic design parameters (i.e., linkage ratio and base width among others) and the differences between the manipulation workspace and the actual usable workspace have been studied for linkage-based fingers [20]. One of the key design parameters associated with the design of stable robotic grippers that are optimized for precision grasps, is the palm width as proposed by Leddy and Dollar [21]. This study also suggests that grasp stability is optimized in underactuated hand and gripper designs when the palm width and the finger length are equal. Bircher *et al* examined the caging ability of underactuated hands and concluded that the palm width should be "just right" (not too small or too large) to allow for effective caging grasps [22]. For example, if the palm width is too small, larger objects come in contact with the proximal phalanges first and are pushed out while the fingers close. This indicates that a variable base width would be ideal for different objects.

The range of object sizes that need to be grasped and manipulated also determines the ideal link dimensions and inter-finger distance. Liarokapis and Dollar investigated the relationship between the object sizes and manipulation range of motion [10], showing that a given hand can have different manipulation capabilities for different object sizes and shapes. Hence, the object set to be grasped and manipulated plays a vital role in determining the dexterous manipulation capabilities of a gripper or hand and should be considered while optimizing the design parameters. Ciocarlie *et al* optimized the link dimensions to extend the size range of objects a gripper can kinematically enclose / entrap, through a combination of random search and gradient descent with numerical gradient computation [3]. Finally, the optimal joint coupling for a wide range of object sizes and positions has been identified to optimise gripper performance [17].

Although all the aforementioned studies optimized one or more kinematic parameters of robotic grippers, the objective function varied widely focusing on different characteristics, such as: i) the grasping performance [15], ii) the gripping forces [13], [14], iii) the grasping and manipulation workspace [20], iv) the dexterous manipulation performance [10], among others. Moreover, all these optimisation studies were limited to specific robotic gripper designs, specific task and application conditions, and considered only specific and limited object sets. From the examined related work, it is evident that the link dimensions, palm width, and the interaction between the fingers are the key parameters that contribute towards the manipulation capabilities of a robotic hand or gripper. These parameters depend on the object set that needs to be manipulated. Also, it must be noted that there cannot be an one-size-fits-all gripper for all object sizes. All the grippers in the aforementioned studies had a fixed pre-determined finger-base position and inter-finger distance limiting their grasping and manipulation capabilities to a particular object size range. The multi-modal gripper proposed in this study on the other hand has reconfigurable finger base frames and can operate in both an adaptive grasping configuration and parallel-jaw gripper configuration. This enables the gripper to choose the right configuration and vary the inter-finger distance, grasping and manipulating objects of varying sizes.

The rest of the paper, is organized as follows: Section III details the dexterous manipulation workspace analysis, the outcomes of the analysis, and their implications, Section IV presents the design of the proposed multi-modal robotic gripper, Section V presents the results of the grasping and manipulation experiments that have been conducted with the proposed robotic gripper, while section VI concludes the paper and discusses some possible future directions.

III. MANIPULATION WORKSPACE ANALYSIS

The workspace analysis of the various two-fingered robotic gripper designs is defined as a constrained multi-parametric optimization problem. We employ a parallel multi-start search algorithm to solve this problem. The objective is to find the ideal link lengths and inter-finger distance of a two fingered gripper that maximizes its manipulation capability for a set of different object sizes.

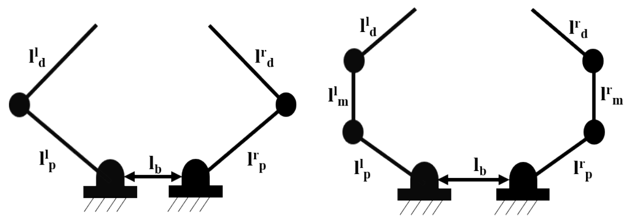


FIGURE 2. Kinematic structure of a gripper model with two phalanges (left model) and a gripper model with three phalanges (right model). l_b is the distance between the finger bases and l^l_p, l^l_m, l^l_d, l^r_p, l^r_m and l^r_d represent the left proximal, left middle, left distal, right proximal, right middle, and right distal phalanges, respectively.

Four different categories of two-fingered grippers are analysed: i) symmetric fingers with two phalanges, ii) asymmetric fingers with two phalanges, iii) symmetric fingers with three phalanges, and iv) asymmetric finger with three phalanges.

A. DESIGN VARIABLES AND MANIPULATION CONSIDERATIONS

A kinematic model is created for each of the grippers with the link lengths and base width as variables. The kinematics models of symmetrical grippers with two and three phalanges are presented in Figure 2. Each Degree of Freedom (DoF) can be actuated independently of the other DoFs as the models are considered to be fully actuated. The five variables for the robotic grippers with the two phalanges per finger, are the four link dimensions of the proximal and distal phalanges of the two fingers and the distance between the finger base frames. The seven variables for the robotic grippers with the three phalanges, are the six link dimensions of the proximal, middle, and distal phalanges of the two fingers and the distance between the finger base frames. The object length is added as a constraint. In order to limit the design space that needs to be explored and prevent exploring options that are unrealistic or non-feasible, the following were taken into consideration:

- The total length of each finger was constrained to have an upper limit.
- This study only analyses pinch grasps and manipulation motions that can be executed by the fingertips.
- The in-hand manipulation tasks involving the proximal phalanges of the fingers are excluded from this analysis.
- Equilibrium point manipulation was hypothesized that is executed with point contacts in each finger. Rolling contacts and the associated slipping that may occur were hypothesized to be of minimal significance for the purpose of this work. Such phenomena are also hard to model and simulate.
- For the symmetrical designs of robotic grippers with two and three phalanges, symmetry is set as a constraint.
- The object is added as an extra link to one of the fingers. Thus dexterous manipulation is modelled as the inverse kinematics problem of finding the configuration of the

finger with the extra object link that can reach the tip of the other finger (if such a configuration exists).

B. PROBLEM FORMULATION

The volume of the dexterous manipulation workspace is given by the function $V(\mathbf{x})$ where $\mathbf{x}$ is a vector containing the variables presented in the previous section. More precisely, the volume is calculated using the resulting set of points that define all possible, reachable positions of the manipulated object and these points are calculated using the forward kinematics of the system. Thus, the optimization problem to maximize the volume of the manipulation workspace by finding the ideal link lengths and distance between the finger base frames can be written as presented in Eq. (1)-(7),

$$x^* = \underset{x}{\operatorname{argmin}} - V(x) \quad s.t. \tag{1}$$

$$l_b = l_{total} - (l^l + l^r) \tag{2}$$

$$\left\{ \begin{array}{l} l_p^l + l_d^l =< l_{max}^l \\ l_p^r + l_d^r =< l_{max}^r \end{array} \right\} if\ n_p = 2 \tag{3}$$

$$\left\{ \begin{array}{l} l_p^l + l_m^l + l_d^l =< l_{max}^l \\ l_p^r + l_m^l + l_d^r =< l_{max}^r \end{array} \right\} if\ n_p = 3 \tag{4}$$

$$l_p^l = l_p^r \tag{5}$$

$$l_m^l = l_m^r \tag{6}$$

$$l_d^l = l_d^r \tag{7}$$

where n_p is the number of phalanges and the maximum link dimensions for left (l_{max}^l) and right (l_{max}^r) fingers are limited to the sum of link lengths for the left finger and the sum of the link lengths and the virtual object length for the right finger. Finally, l_b is the distance between the finger bases calculated as the difference between the total link dimensions (including the object length) and finger lengths. Symmetry between the left and right fingers is added as a constraint, as seen in Eq. (5)-(7).

The proposed formulation seeks to identify the ideal link lengths and the distance between the finger base frames that maximize the dexterous manipulation workspace. The gripper model was created using the MATLAB Robotics toolbox [23]. The initial dimensions of the gripper and range of object sizes are provided as user-defined inputs. An *fmincon* solver is then used to search the optimization space using a non-linear gradient ascent. The optimisation speed was optimized using the MATLAB's parallel solver by initiating the parallel pool and the multi-start algorithm. The parallel pool employs multiple solvers each initiating from a random start point spread across the search space to solve the optimization problem in parallel. Apart from ensuring that the optimization does not exit on a local maximum, the multi-start algorithm also increases the optimization speed considerably. Once the function tolerance is reached, the solver exits with a positive flag providing the optimal link lengths for a given object size.

C. MANIPULATION WORKSPACE GENERATION

The dexterous manipulation workspace is calculated as the space occupied by all possible positions that the object can attain during the execution of in-hand manipulation in the plane. These positions are derived as a set of points, a planar point cloud. The bounding volume of the point cloud is calculated using the *alphaShape* method, which formalises the abstract shape of the given set of points using Delaunay triangulation [24].

D. MANIPULATION WORKSPACE IMPLICATIONS

The manipulation workspace was significantly influenced by each of the design variables and constraints. The manipulation workspace for the robotic gripper with the three phalanges is bigger than the robotic gripper with the two phalanges when they have the same total finger-length. This can be attributed to the increased control over the workspace that is provided by the extra link. The optimal ratio of the lengths of the proximal and distal phalanges for the symmetrical gripper with the two phalanges averaged at 0.61 and 0.39, respectively. For symmetrical design with the three phalanges the ratio of proximal, middle, and distal dimensions averaged at 0.29, 0.35, and 0.36 respectively. When the constraint of symmetry was removed, the right finger ratios changed to 0.37, 0.28, and 0.33 for the proximal, middle, and distal phalanges, while the respective ratios for the left finger averaged at 0.38, 0.3, and 0.32. For the gripper with the two phalanges, the right finger ratio remained similar to the symmetrical gripper averaging at 0.60 and 0.40 for the proximal and distal phalanges respectively. The left finger dimensions converged to 0.57 and 0.43.

For all the optimisation cases the distance between the finger bases converged to zero. This could indicate that the manipulation capability is inversely proportional to the inter-finger distance. To further investigate this effect, the manipulation workspace for varying inter-finger distance was calculated for the original finger dimension. The results of this computation are presented in Figure 3i, Figure 3ii, Figure 4i, and Figure 4ii showing that halving the inter-finger distance results in improved manipulation workspace volume and causing a change in the workspace shape as well. The shape of the workspace varied not only for the different categories of grippers but also with each object as seen in these plots. This can be attributed to the fact that the grasping configuration changes with the objects as well as with the inter-finger distance. When the base frames are closer, the fingertips can stay in contact for a greater range of configurations, allowing the object to be displaced to a wider range of positions to the left and right of the fingers and resulting in a larger manipulation workspace volume. As the finger bases move further away from each other, this displacement region keeps decreasing. Once the base frames move further than a certain limit the object can only be manipulated in a narrow space between the fingers.

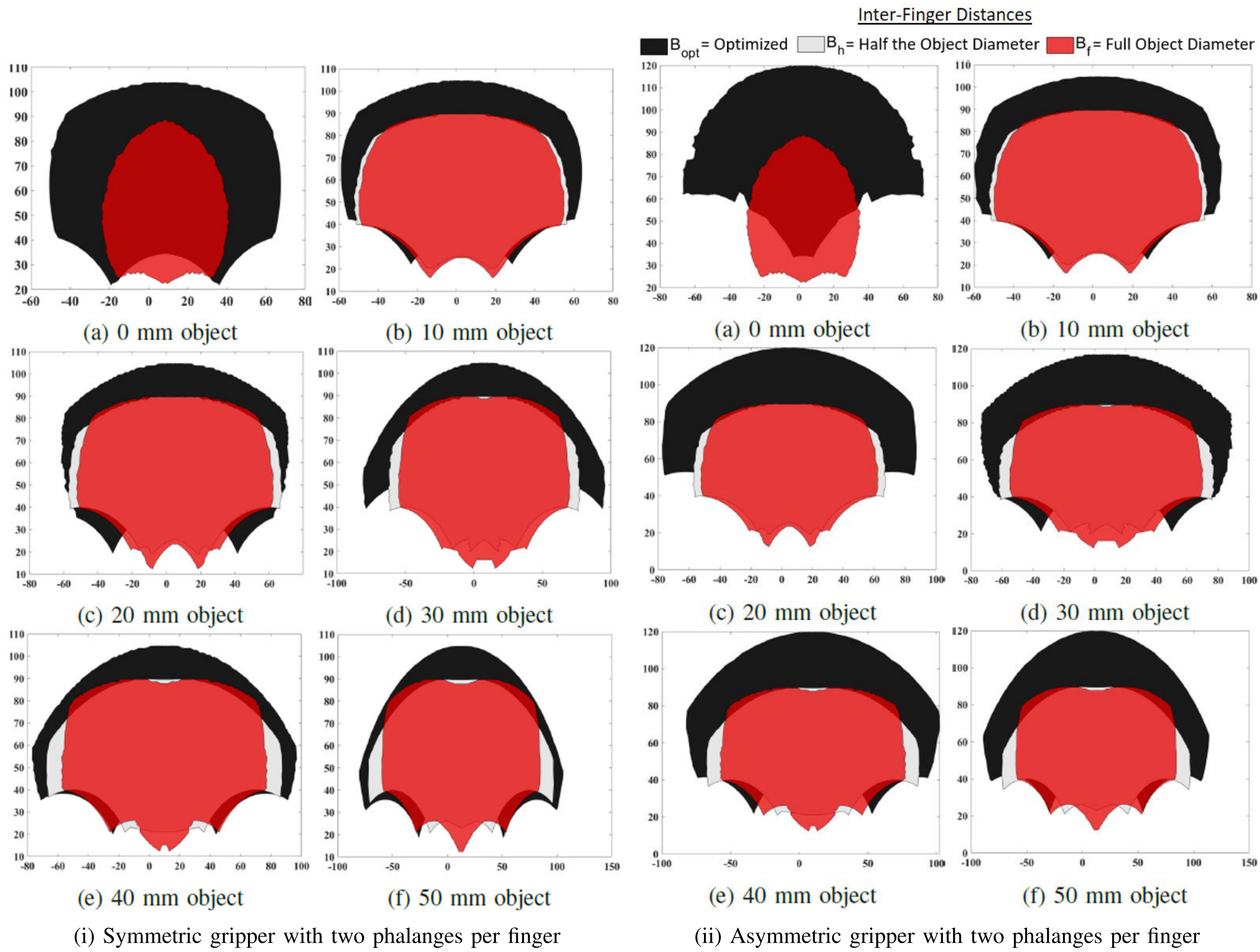


FIGURE 3. Workspace comparison results for symmetric and non-symmetric grippers with two phalanges per finger and different object diameters.

It can also be observed that the workspace generated by the asymmetrical finger configurations are asymmetrical as well. This effect is more evident in fingers with three phalanges. Figure 4ii presents the workspace generated by fingers with three phalanges under optimal symmetrical and asymmetrical link ratios. It shows how the workspace generated by asymmetrical fingers are askew and irregularly shaped, while the symmetrical workspace is uniformly shaped. As the fingers are of different dimensions the centre between the fingers is altered making the workspace to favour one half over the other, resulting in abnormal workspaces with rough edges. The rough edges that change abruptly throughout also mean that the grasp robustness might be compromised at these regions and the fingers may lose contact with the object as they traverse through such regions owing to sudden jerk motions. Though the volume is comparable to the symmetrical configurations, the asymmetry would make the control difficult and decision would need to be made on which finger or half of the workspace is to be favoured on a case by case basis. As this seems to cause difficulties under practical conditions, it is better to opt for the symmetrical configurations of robotic grippers that result to symmetric dexterous manipulation workspaces with smoother edges.

The comparison also shows that the maximum workspace volume was achieved with optimal link ratios and zeroed inter-finger distance. It can be noticed that the different achievable workspaces are not always a subset of the optimized workspace. The differences in workspace shapes and sizes mean that the fingers can manipulate the objects in different regions of the achievable workspaces when different inter-finger distances are employed. In order to determine the percentage of area that can be covered with a certain inter-finger distance, we calculated the ratio of the individual workspace to the union of all workspaces (combined workspace) the value of which was always less than 1. Even though the ratio was higher for optimized workspaces indicating their ability to cover a major section of the union of workspaces, they still couldn't represent the entire union. The results of these comparisons for all the fingers with two and three phalanges are presented in Table 1. Also, it can

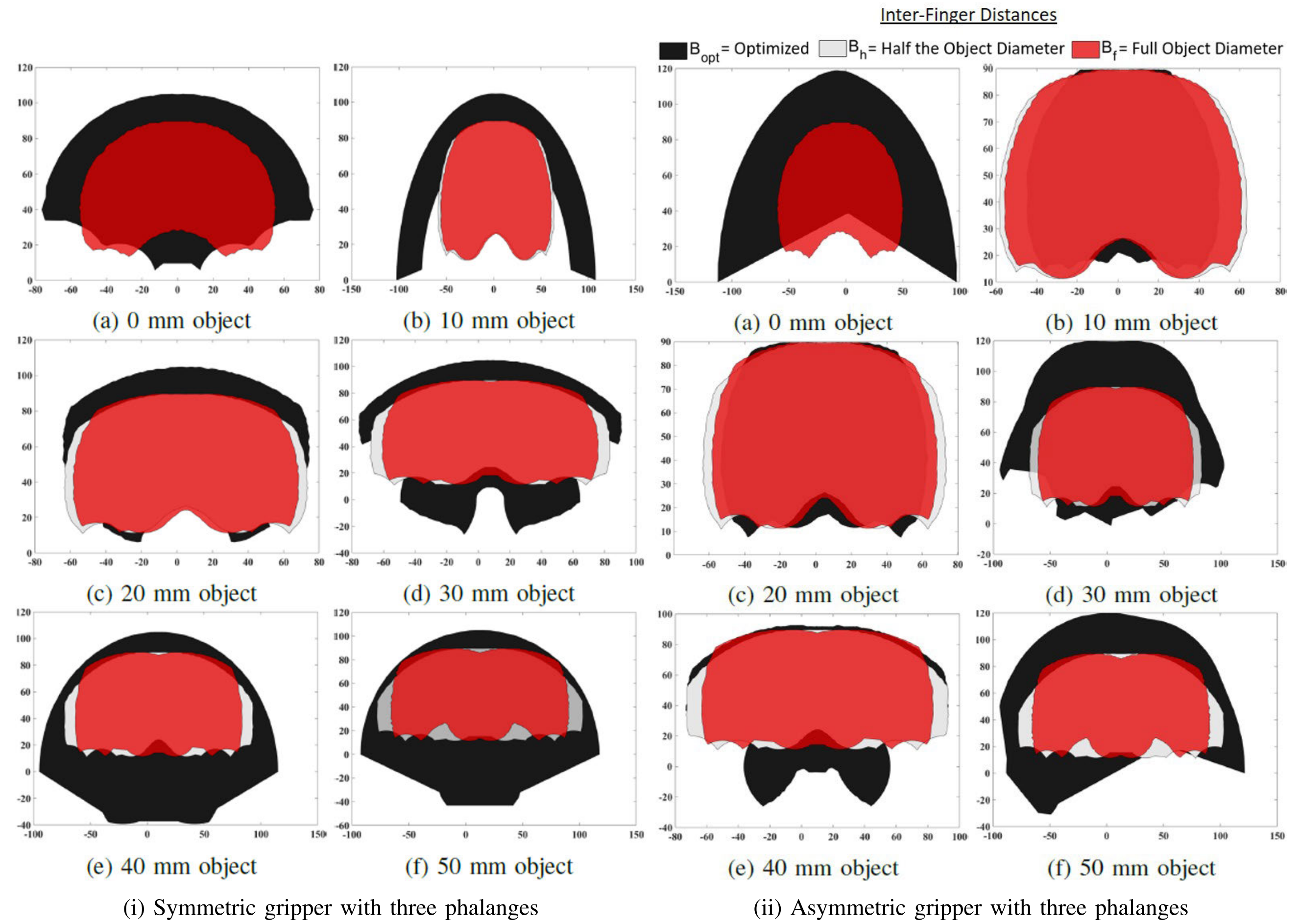


FIGURE 4. Workspace comparison results for symmetric and non-symmetric grippers with three phalanges per finger and different object diameters.

TABLE 1. Manipulation capability results for various types of grippers and varying object diameters.

Manipulation Capability Metric	$WS_{opt} / \bigcup_{i=1}^{n} WS_i$					
Object Length	0 mm	10 mm	20 mm	30 mm	40 mm	50 mm
Symmetric gripper with 2 phalanges per finger	0.9745	0.9302	0.8627	0.7955	0.8975	0.8983
Asymmetric gripper with 2 phalanges per finger	0.8137	0.933	0.8728	0.8429	0.8717	0.8827
Symmetric gripper with 3 phalanges per finger	0.9692	0.4934	0.9169	0.8541	0.7602	0.8415
Asymmetric gripper with 3 phalanges per finger	0.5821	0.4065	0.9537	0.8384	0.932	0.9

TABLE 2. Grasping (G) and Manipulation (M) capabilities of the multi-modal gripper for five different spheres employing the adaptive gripper mode (at base widths: 0 mm, 30 mm, 70 mm, and 110 mm) and the parallel jaw mode.

Object	Adaptive (0 mm)		Adaptive (30 mm)		Adaptive (70 mm)		Adaptive (110 mm)		Parallel Jaw	
	G	M	G	M	G	M	G	M	G	M
Marble	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Golf Ball	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Racquetball	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Baseball	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Softball	Y	Y	Y	Y	Y	Y	Y	Y	Y	N

be noticed that in the workspace plots there are gaps and regions that are not connected in some optimized workspaces which are included in workspaces generated by non-optimal inter-finger distances. The hand would lose contact with the object in these regions (under normal circumstances), rendering the manipulative space as a set of non-connected regions. Hence, in order to maximize the dexterous manipulation capability of a two fingered gripper, the distance between the finger base frames should be adaptable, enabling the fingers to reach workspace regions generated by varying

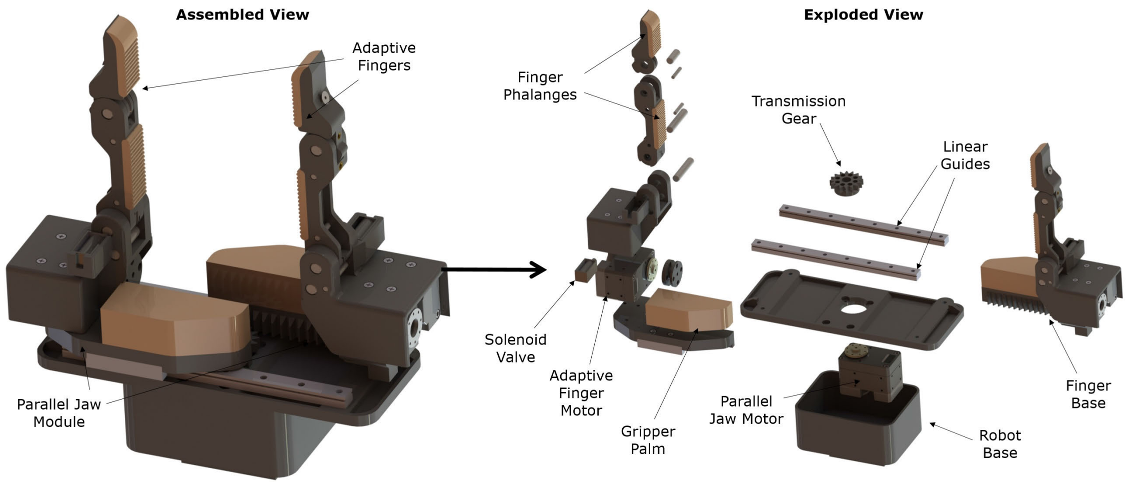


FIGURE 5. The assembled and exploded views of the proposed multi-modal robotic gripper.

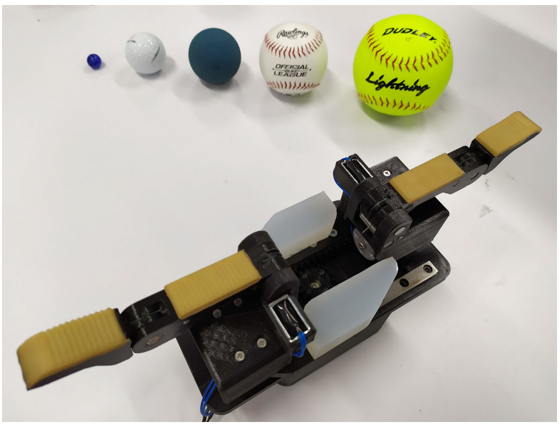


FIGURE 6. The objects used were: a marble (diameter: 16 mm), a golf ball (diameter: 42.7 mm), a racquetball (diameter: 55.3 mm), a baseball (diameter: 73.3 mm), and a softball (diameter: 96 mm).

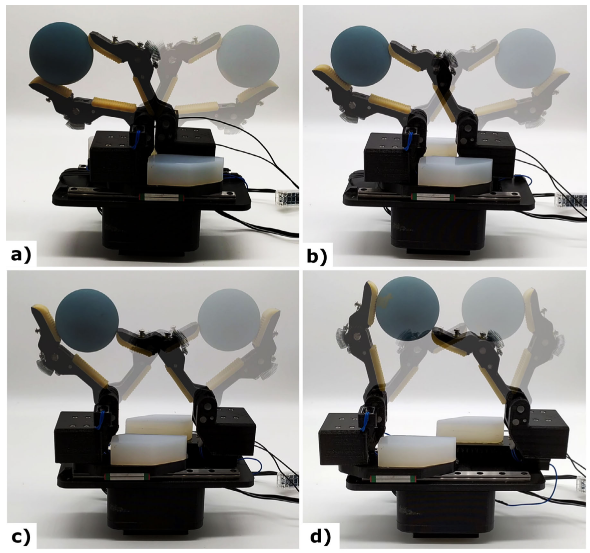


FIGURE 7. Dexterous manipulation of a racquetball when the inter-finger distances are: 0 mm (7a), 30 mm (7b), 70 mm (7c), and 110 mm (7d).

inter-finger distances. Taking all these into account, the gripper described in Section IV has been designed with reconfigurable finger base frames so as to increase the volume of the manipulation workspace.

IV. DESIGN

The ideas derived from the dexterous manipulation workspace analysis were employed for the development of a multi-modal robotic gripper that is composed of two different modules: a parallel jaw module and two adaptive robot fingers (as shown in Figure 5). A Dynamixel XM430-W350 motor, two linear guides, and a transmission gear are used to construct the gripper base that creates the parallel jaw module. The two adaptive finger units are mounted on linear rails allowing them to slide to and away from the gripper center thereby allowing the inter-finger distance between the finger bases to vary between 0 mm to 110 mm. The parallel jaw motor in the gripper base is coupled to a rack in the finger units for force transmission. The design of the tendon-driven finger unit is based on the adaptive robot fingers of the Model O gripper of the Yale Open Hand project [25]. Each finger is actuated using a Dynamixel XM430-W350 motor that is enclosed in the finger unit. A locking mechanism is created using a solenoid valve that allows the fingers to be locked perpendicularly to the base thereby converting the gripper to act as a parallel jaw gripper. This allows the gripper to exert higher grasping forces owing to the lack of post-contact reconfiguration in parallel jaw grippers [26]. When this mechanism is not activated, the finger has a bigger aperture for caging objects more easily, like adaptive grippers [25]. This allows the fingers to conform to the object's surface resulting in a more stable grasp owing to the increase in the number of contact points. Thus, the proposed robotic gripper exploits the advantages of both these grasping modes (adaptive and parallel jaw).

FIGURE 8. Comparison for different types of grasps that are executed with the proposed gripper.

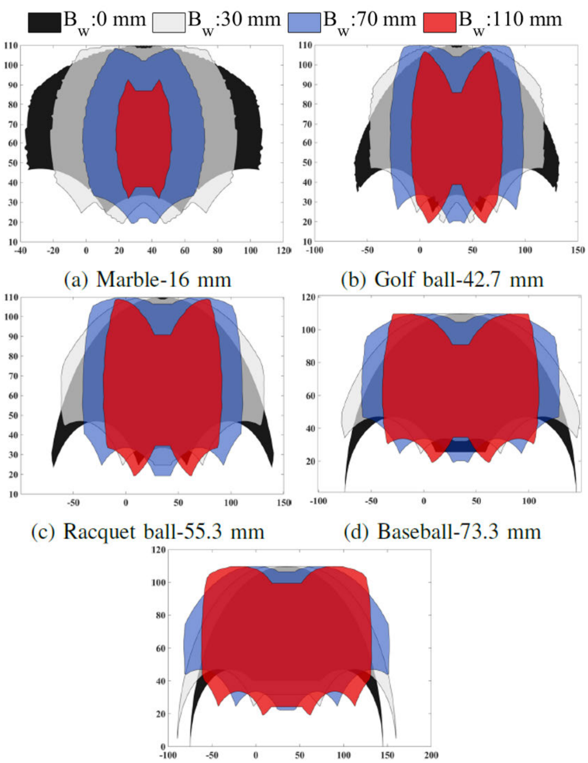


FIGURE 9. Results for the multi-modal robotic gripper with reconfigurable finger bases - Comparison of workspace achieved for spherical objects presented in Figure 6 that have different diameters and are separated by various base widths: B_W= 0 mm, 30 mm, 70 mm, and 110 mm.

V. RESULTS AND DISCUSSION

The ability of the proposed gripper to manipulate objects of varying sizes is validated using the object set shown in Figure 6. This object set is composed of spherical objects of varying texture and diameter ranging from 16 mm (marble) to 96 mm (a softball). The results of this experiment are presented in Table 2 and show that the gripper can successfully grasp and manipulate the objects while the fingers were locked at various positions with the inter-finger distance varying from 0 mm to 110 mm in the adaptive grasping mode. Although the gripper managed to robustly grasp all the objects using the parallel jaw grasping mode, object manipulation was not feasible. The manipulation workspace for a racquetball at its workspace extremes during different inter-finger distances is presented in Figure 7. It shows the variation in workspace shape when the base width is altered from 0 mm through to 110 mm. It clearly demonstrates that the displacement of the object is larger when the inter-finger distance is 0 mm and decreases as the inter-finger base distance approaches 110 mm, indicating that the manipulation workspace volume is inversely proportional to the inter-finger distance. The figure clearly shows the variation in workspace shape when the base width is altered from 0 mm through to 110 mm and that all workspaces have unique regions. Hence, the union of the workspaces is always greater than any of the individual workspaces, as shown in Table 3. It can also be noted from Table 3 that when the phalange ratio is fixed, the optimal workspace is achieved only with a lower

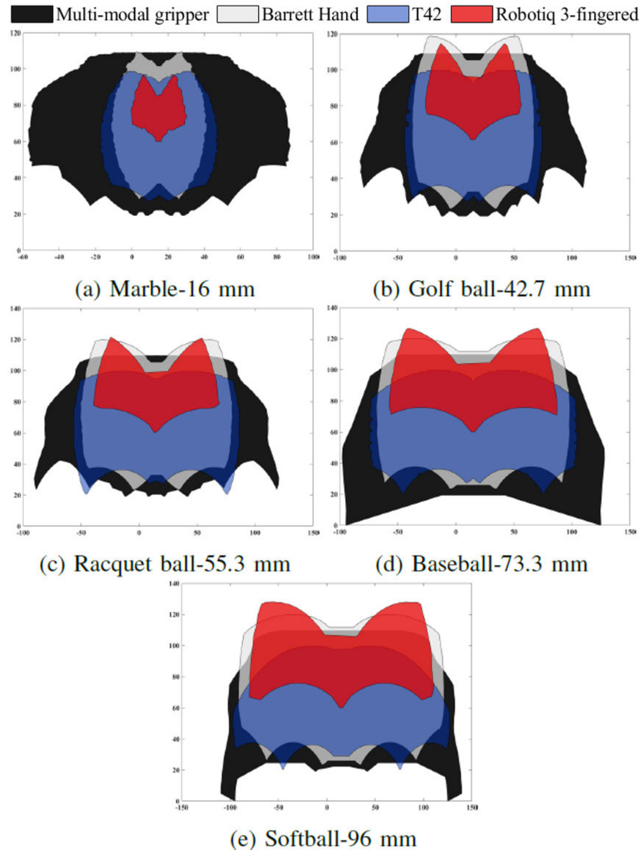
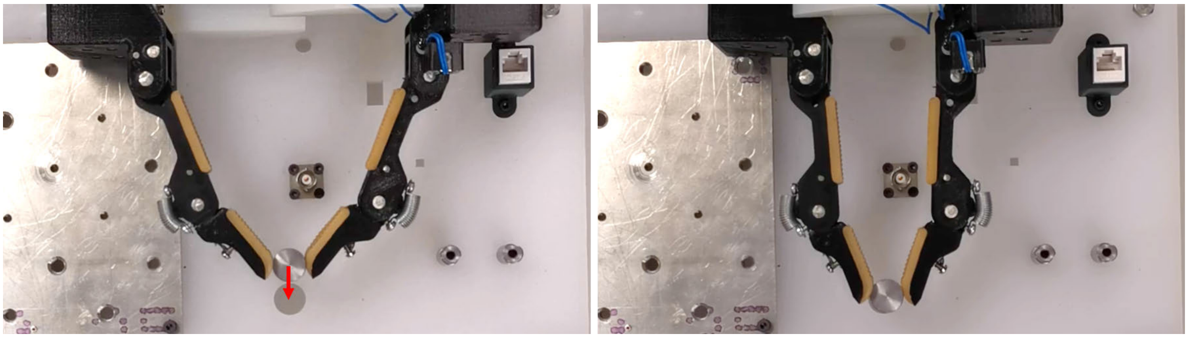
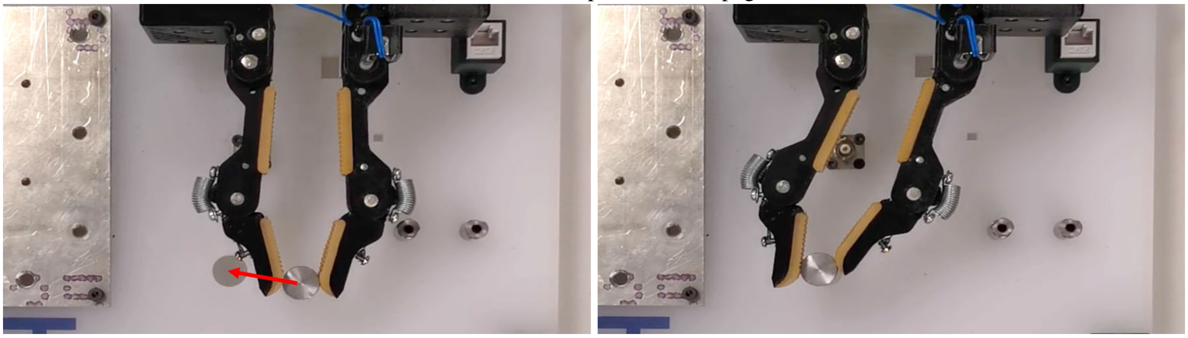


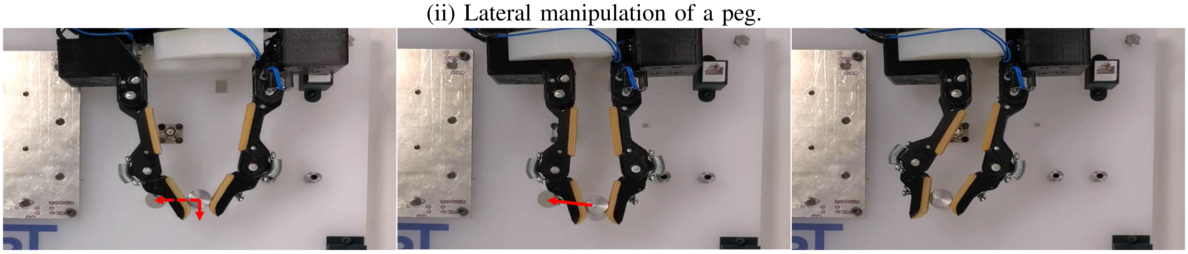
FIGURE 10. Comparison of the workspaces achieved by the multi-modal gripper, the Barrett hand, the T42 gripper, and the Robotiq 3-fingered adaptive robotic gripper for the spherical objects presented in Figure 6 that have different diameters.



(i) Vertical manipulation of a peg.



(ii) Lateral manipulation of a peg.



(iii) Combined manipulation of a peg to cover blind space in manipulation workspace.

FIGURE 11. Demonstration of a vertical and horizontal manipulation capability of the multi-modal gripper while performing a peg in hole task.

inter-finger distance. Moreover, the configuration space of the gripper gets limited when trying to manipulate an object that is much bigger than the gripper fingers. If the inter-finger distance is increased, the object can be approached by the distal fingertips from the sides, allowing it to manipulate the object freely. Hence variation of the inter-finger distance is necessary for improving the overall manipulation capability when the ratio of the phalanges is fixed. This can only be achieved by a gripper capable of varying the base-width/inter-finger distance online, while maintaining contact with the object, as demonstrated in this study. Figure 8 demonstrates the effectiveness of the gripper in executing various types of grasps on a number of objects of varying sizes and shapes using the adaptive and the parallel jaw mode. The manipulation workspace of spherical objects with varying diameter and inter-finger distances is presented in Figure 9.

The unique vertical and lateral manipulation capability of the gripper is demonstrated in Figure 11i and Figure 11ii. While the gripper can manipulate the objects along a straight line vertically, the lateral movement is along an arc like most grippers resulting in a blind space in the gripper workspace. The multi-modal gripper overcomes this limitation by combining the vertical and lateral manipulation movements, increasing the overall available manipulation workspace as presented in Figure 11iii. In order to compare the efficiency of the multi-modal gripper against some of the commonly used grippers in literature, the kinematic models of the multi-modal gripper, the Barrett hand, the T42 gripper, and the Robotiq 3-fingered adaptive robotic gripper were prepared in MATLAB and the planar manipulation workspaces for the objects presented in Figure 6 were generated. The workspace generated by these grippers for the various objects can be seen in Figure 10 and the results of this simulation calculated in mm^2, are presented in Table 4. The workspace generated by the multi-modal gripper is significantly larger compared to the workspaces of the other grippers for the entire set of objects. This can be attributed to the reconfigurable finger bases of the gripper that enable it to adapt to various object sizes and cover a wider range of workspace regions with any given object. This clearly demonstrates the improved manipulation capability of the proposed gripper.

TABLE 3. Results of the multi-modal robotic gripper with reconfigurable finger bases. The ratio of optimised workspace (WS_{opt}) to the union of all the workspaces($\bigcup_{i=1}^{n} WS_i$) generated for spherical objects of varying object diameter at base width B_w= 0 mm, 30 mm, 70 mm, and 110 mm.

Object Name	Object Diameter (mm)	$WS_{opt} / \bigcup_{i=1}^{n} WS_i$			
		B_w=0 mm	B_w=30 mm	B_w=70 mm	B_w=110 mm
Marble	16	0.8703	0.8234	0.5107	0.1509
Golf ball	42.7	0.8831	0.7661	0.76	0.4556
Racquet ball	55.3	0.7558	0.8512	0.81	0.5421
Baseball	73.3	0.6201	0.7115	0.745	0.5835
Softball	96	0.5425	0.6254	0.7939	0.7413

TABLE 4. Workspace comparison of the multi-modal gripper with the Barrett hand, the T42 gripper, and the Robotiq 3-fingered adaptive robotic gripper.

Object Name	Object Diameter (in mm)	Planar Manipulation Workspace (in mm^2)			
		Multi-modal	Barrett Hand	T42	Robotiq 3-fingered
Marble	16	9853.25	3132.09	3503.70	662.94
Golf ball	42.7	12373.54	8015.71	6862.21	2527.41
Racquet ball	55.3	14103.66	10056.80	9035.30	3663.85
Baseball	73.3	17888.25	13338.65	9814.61	5626.74
Softball	96	18849.60	16718.32	12522.67	8446.33

A video presenting experiments conducted with the proposed multi-modal robotic gripper can be found at the following URL:

https://newdexterity.org/multimodalgripper

VI. CONCLUSION

This paper proposed a framework for finding the optimal link dimensions and inter-finger distance (for a given object) for robotic grippers that are symmetric or asymmetric with two and three phalanges per finger. The optimization problem was designed so as to maximize the manipulation workspace volume for a wide range of objects by parametrizing the link dimensions and inter-finger distance and searching the design space for the optimal values of these parameters. This was performed using a parallel multi-start search algorithm to solve the multiparametric optimization problem. The optimization provided us with the optimal link ratios for all four gripper configurations examined. The workspace analysis results demonstrate that for a fixed finger dimension, the manipulation workspace is inversely proportional to the distance between the fingers and reaches its maximum volume at zero inter-finger distance. The workspace varied widely in shape and volume for varying link ratios and inter-finger distances. The achievable workspaces had unique regions and some of them had gaps or disconnected regions, indicating that the union of these workspaces is always greater than any individual workspace and that a gripper capable of covering the union of these workspaces is required so as to maximize grasp robustness and improve manipulation performance. Thus, a gripper with a reconfigurable base was designed and developed and its efficiency was experimentally validated. The gripper was fabricated with an optimal link ratio and was mounted on a parallel jaw module that allowed varying the inter-finger distance from 0 mm to 110 mm. The design is equipped with lockable joints that allow transitioning between an adaptive grasping configuration and a parallel jaw grasping configuration. The proposed gripper achieved a great increase in the volume of the achievable manipulation workspace without sacrificing grasping robustness and efficiency. It demonstrated clearly that for a given link ratio, the manipulation workspace is maximum when the inter-finger distance is zero and decreases as the finger bases move away from each other. This can easily be extended to other robotic hands as the parameters and features being optimized here are applicable to all robotic end-effectors.

In terms of potential future work, the framework will be extended to grippers with more phalanges and more fingers. Another key priority would be check how the inter-finger distance affects the workspace of multi-fingered hand designs. We also intend to identify and optimize other key design parameters.

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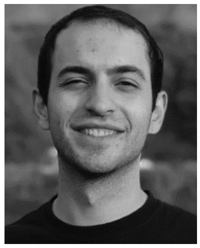

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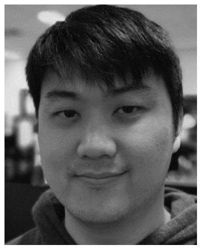

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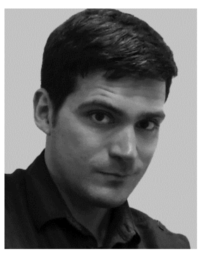

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