Supplementary: LEAP Hand. Dexterous, Low-Cost, Robust, and Anthropomorphic Hand for Robot Learning

I. Detailed Cost Analysis

Please see table I for a detailed Bill of Materials and breakdown of the cost to create the hand. This is accurate pricing as of the paper submission. While we assert that the LEAP Hand is low cost, we acknowledge that it is still not affordable for everyone such as hobbyists. We will continue to strive to bring down the price of further versions of the hands. However, LEAP Hand is cheaper than many other roobt hands currently in use in research today such as the Allegro Hand ($16k).

II. Assembly Instructions

The assembly instructions will be released upon acceptance of the paper at http://leap-hand.github.io/ The hand only requires simple hand tools to build and can be built in as short as 4 hours.

III. leap-hand 5

While LEAP has 4 fingers, our 5-fingered variant, LEAP-5, adds even more human-like qualities; see Figure 3. This hand features five fingers for firm grasping which is a rarity for robot hands. It contains an additional joint in the palm that enables the palm to fold-in like a human palm. As the palm wraps around the objects, it brings the fingers closer to facilitate a stronger grasp. We experiment with this using the LEAP-C Hand morphology. Please see further videos at http://leap-hand.github.io/

IV. Grasping Analysis

Each of the hands is compared in their ability to grasp a variety of YCB objects [1]. We place the object starting in the palm and then gradually command a contracting force to each of the hands. We try 12 different starting angles spread around the object until the best angle is found. We then record the number of times the robot hand can grasp the object at that angle. The object is successfully grasped if the hand can support the object and resist at least 10N of force. Please see the videos at http://leap-hand.github.io/

Object	Quantity	Total
Dynamixel XC330-M288	16	$1500
FPX330 Brackets	32	$80
U2D2 Control PCB	1	$20
5v 20A Power Supply	1	$25
14 AWG Cabling	1	$20
PLA Printer Plastic	N/A	$10
3D printer	1	$250
Total		$1900

TABLE I: We present the bill of materials of our hand. The total cost is under $2000. Further details and purchasing links are on our website at http://leap-hand.github.io/.

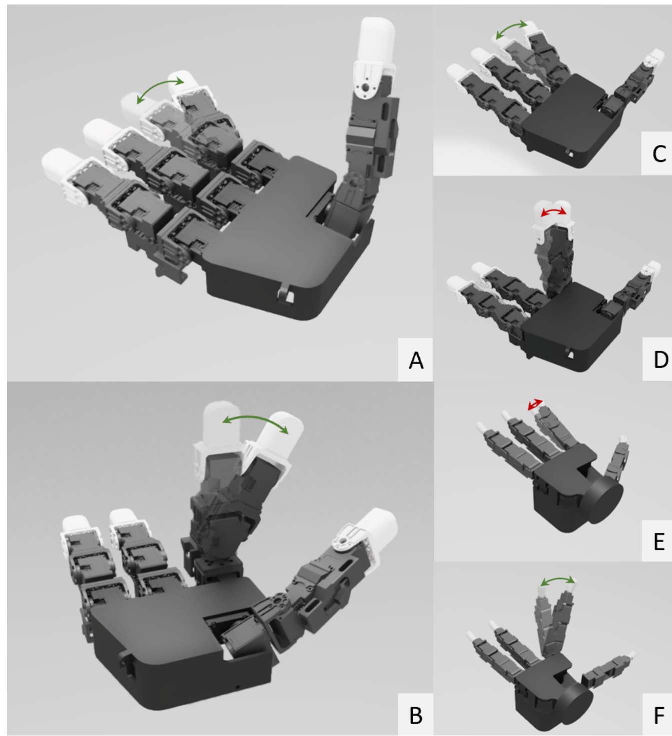

Fig. 1: Further analysis of the kinematic tree between LEAP Hand (A,B), LEAP C-Hand (C,D) and Allegro Hand. In LEAP Hand, the MCP side is kinematically after the MCP forward. This allows it to be effective in both the finger up and down configurations. LEAP C-Hand has the MCP side before the MCP forward, which limits its side to side in the up configuration. Allegro Hand has pronation and suppination, which is rotation around the base of the joint. This is useful in the up configuration but not in the down.

Table II shows leap-hand can grasp 9/10 objects, surpassing all other hands, due to its proper abduction and adduction joints that allow the hand to adapt to the object. Additionally, contains enough strength to support heavy objects such as the pan (725 g) and the drill (610 g). LEAP-5 with its articulated palm joint in the middle of the palm, as seen in Figure 3, can wrap around objects firmly and grasp even the soccer ball. Allegro Hand is much weaker and does not have human-like abduction and adduction joints, which means it cannot properly grasp the orange or heavier objects. D'Manus [2], while strong, is very large and does not have a proper morphology for grasping

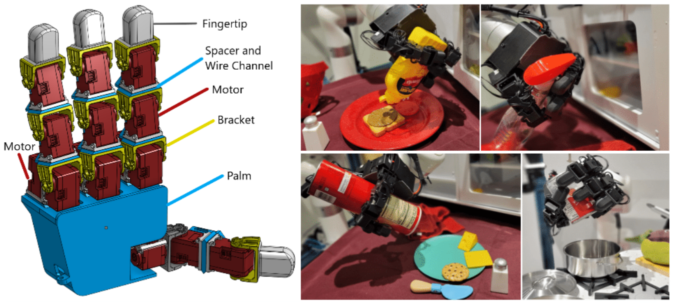

Fig. 2: LEAP Hand is suited for diverse dexterous tasks and is low-cost, robust, has a human-like form factor, and will be open-sourced to democratize machine learning for dexterous manipulation.

YCB Object	# Successes (out of 10 trials) LEAP	LEAP-5	Allegro	Inmoov	D'Manus
Soup Can	10	10	9	9	0
Mustard Bottle	10	10	7	2	0
Mug	10	10	9	7	3
Baseball	10	10	10	8	10
Soccer Ball	1	10	0	0	10
Orange	10	10	9	9	0
Drill	10	10	1	0	10
Pringles Cont.	10	10	10	0	0
Coffee Can	10	10	10	0	10
Pan	9	10	0	0	0
Total	**90**	**100**	**65**	**35**	**43**

TABLE II: **Grasping test.** can consistently grasp 9/10 objects, the best across hands. We find the best grasp pose for each hand and attempt 10 trials per object.

smaller objects. Inmoov [3], while the most human-sized, only has 5 DOF with poor grip force so it cannot grasp many objects.

V. Teleoperation from Manus Glove

For accurate grasping in the grasping test, we use the Manus Meta Quantum Metagloves [4] which is an $8000 tracking

Fig. 3: **LEAP-5** variant has 5 fingers and a foldable palm that closes on itself enabling more intricate grasps. Our design's modularity helps scale to 5 fingers with minimal overhead.

Fig. 4: We use the Manus VR glove for accurate teleoperation for the robot hand in the grasping test.

Mocap glove. Each finger is tracked by the glove and returns 4 different angles $\theta_{\mathrm{MCP}_{\mathrm{side}}}, \theta_{\mathrm{MCP}_{\mathrm{fwd}}}, \theta_{\mathrm{PIP}}, \theta_{\mathrm{DIP}}$ using hall effect sensors with very high accuracy. These angles are mapped directly one-to-one to the robot hand embodiment. Once in the robot hand embodiment, we convert to motor joint angles to scale to the leap-hand.

For the wrist tracking we use a similar method to [5] but instead of the image, we use the wearable SteamVR trackers as the base frame and the wrist frame. These trackers use time of flight from 4 SteamVR Lighthouses that are placed near the operator. The transform between these two trackers is transferred to the robot frame by rotating and scaling them heuristically. For instance, we want the hand on the robot to be facing the same way as the human hand at all times. Inverse kinematics is used to map the end effector position to joint angles for the xArm. Safety checks, including one that uses dynamic force feedback on the arm, are conducted so that the arm does not damage the environment around it. See videos of the system at http://leap-hand.github.io/ .

References

[1] B. Calli, A. Singh, A. Walsman, S. Srinivasa, P. Abbeel, and A. M. Dollar, "The ycb object and model set: Towards common benchmarks for manipulation research," in *2015 International Conference on Advanced Robotics (ICAR)*, 2015, pp. 510–517. 1

[2] M. Ahn, H. Zhu, K. Hartikainen, H. Ponte, A. Gupta, S. Levine, and V. Kumar, "ROBEL: RObotics BEnchmarks for Learning with low-cost robots," in *Conference on Robot Learning (CoRL)*, 2019. 1

[3] "Inmoov hand," https://inmoov.fr/. 2

[4] "Manus," https://www.manus-meta.com, note=Accessed on 2022-11-28. 2

[5] A. Sivakumar, K. Shaw, and D. Pathak, "Robotic telekinesis: Learning a robotic hand imitator by watching humans on youtube," 2022. 2