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Reconfigurable Underactuated Adaptive Gripper Designed by Morphological Computation*

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***Abstract*— Anthropomorphic robotic grippers are required for robots, prostheses, and orthosis to enable manipulation of a priori unknown and variable-shape objects. It has to meet a wide range of sometimes contradictory requirements in terms of adaptivity, dexterity, high payload to weight ratio, robustness, aesthetics, compactness, lightweight, etc. Within this paper, we utilize the morphological computation approach to introduce design for anthropomorphic re-configurable underactuated grippers. The key to fingers' adaptivity is embedded passive variable length links and elastic elements at input joints. Based on this concept, we designed a palm-size five-finger gripper, where 14 DoFs, including thumb, are controlled by just 4 motors, such that it can perform both precision pinch and encompassing power grasps of various objects. The paper describes synthesized linkages for digits, hand design overview, control strategy, and test results of a physical prototype.**

Fig. 1. Physical prototype of the reconfigurable underactuated adaptive (RUA) gripper designed by morphological computation concept

I. INTRODUCTION

The human hand is capable of performing a long list of gestures and grasps due to its morphology [1]. Anthropomorphic robotic grippers are intended to copy the human hand's functionality and appearance. Grippers such as [2], or [3] are able to mimic the human-like motion and act on a similar level of dexterity because they have 20 and 10 degrees of freedom per hand, respectively. However, besides apparent advantages such as versatility to reconfigure motion, the fingers' fully actuated open-chain mechanisms meet a list of disadvantages in terms of weight, cost, and control issues. As a consequence, a heavy and oversized module with multiple motors has to be installed next to the gripper; the module affects the device's weight and dimensions that often meet strict requirements; sophisticated control strategies are needed to control all actuators.

The study aims to propose a design approach to create an adaptive high payload-to-weight ratio robotic hands with a number of degrees of freedom close to what a human hand has, and at the same time minimize the number and size of motors such that they can fit a gripper's palm. To match these requirements, we have shaped a design concept, which is in line with *the physical intelligence concept* [4], [5], i.e. when intelligent system behaviour is achieved not only on software/algorithm level, but also thanks to smart mechanics.

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Our study follows the idea of *morphological computation*, which means that part of 'computation' is delegated to mechanics. In other words, we 'program' desired kinematic and dynamic properties in the mechanical structure of a system, while control laws complexity is set to a necessary minimum to keep natural dynamics controllable in principle [6]. This principle also gives us an 'infinite control bandwidth,' which is a huge advantage if we talk about physical interaction in an unstructured environment, where software-level sensory-motor coordination might not be fast enough.

The design concept of this work builds upon the method proposed by us in [7], when fingers are synthesized as underactuated closed-chain linkages with elastic elements, which can perform both essential types of grasp: precision and encompassing.

Underactuated mechanisms are often used for adaptive grippers since they can automatically adjust objects' shapes without any sophisticated control algorithms. Typically, underactuation in finger mechanisms is introduced through tendon-driven [8] systems or linkages [9]. However, in our work, this behavior is enabled by embedding passive variable length links (PVLL), i.e., two rigid bodies connected via a spring-loaded prismatic joint. It enables dexterous hand design that is light, compact, robust enough to carry out higher payloads, and can be driven by simple position/velocity tracking control algorithms.

This paper shows an elaborated example of how the suggested design procedure can be utilized to synthesize the digits' mechanism and how the entire hand mechanism with actuators can be arranged within a palm-size. The physical prototype of a reconfigurable underactuated adaptive (RUA) gripper is shown in Fig. 1.

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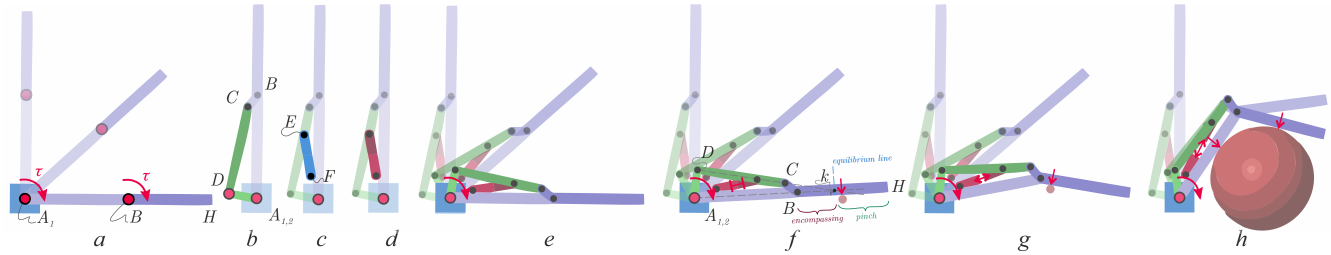

Fig. 2. Design procedure's stages for an index finger: (*a*) defining a fully-actuated open-chain mechanism; (*b*) linkage closure, i.e., transforming the mechanism into closed-chain linkage with the same degree of actuation; (*c*) extending the linkage by adding groups of rigid links to eliminate redundant actuators; (*d*) replacing of selected rigid links from the added links by PVLL; (*e*) index finger bending if there is no interaction with external objects; (*f*) pinch grasp; (*g*-*h*) adaptive grasps. Red dots indicate motors, black dots mean passive joints.

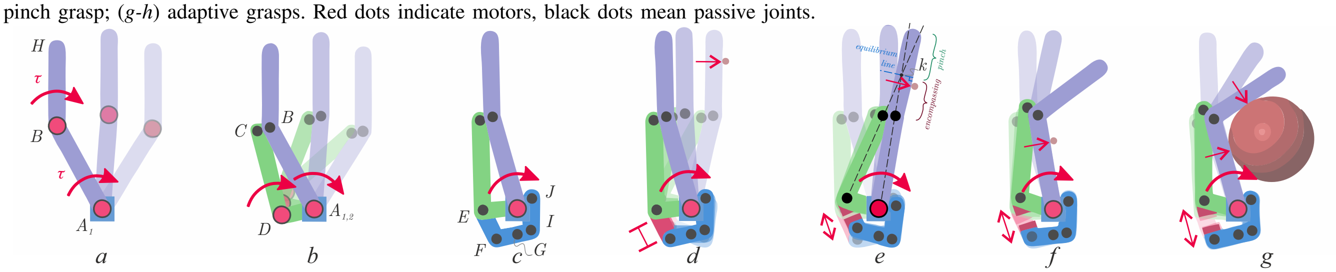

Fig. 3. Design procedure's stages for a thumb: (*a*) defining a fully-actuated open-chain mechanism; (*b*) linkage closure, i.e., transforming the mechanism into closed-chain linkage with the same degree of actuation; (*c*) extending the linkage by adding groups of rigid links to eliminate redundant actuators; (*d*) replacing of selected links from the added links by PVLL, pinch grasp; (*e*-*g*) adaptive grasps. Red dots indicate motors, black dots mean passive joints.

The paper is organized as follows. Section II reveals a step-by-step design procedure to synthesize the digits' mechanisms. Section III is focused on features of the mechanical design of the RUA gripper. Section IV is devoted to the gripper hardware, control algorithms and shows a manufactured physical prototype. The final part concludes with the main points.

II. Linkage synthesis

Synthesis aims to find the mechanical structure of fingers' linkages and set an optimization task for geometric parameters to get the desired behavior. The ability to perform both fundamental grasps: (*a*) a precision pinch grip, in which only the fingertips touch the object accurately, and (*b*) a power adaptive grip, in which all phalanges encompass the object [10], is considered as the desired behavior of the underactuated gripper. A pinch grip is required to interact with tiny objects, while a power grip is needed to interact with larger and more massive objects [9]. To synthesize the linkage, we have used the method proposed in our previous article [7] that has been inspired by the methodology for closed-kinematics linkage topology optimization presented in [11]. Here we give an elaborated overview of synthesis. The method has been used to create all digits of the hand.

Fig. 2 and Fig. 3 show all the stages of the mentioned design procedure. The intuition of the method is the following: (*a*) we define an open-chain linkage that can follow the desired trajectory, then (*b*) we transform it into closed-chain linkage to relocate motors bringing new links, (*c*) we introduce holonomic constraint needed for motors' elimination, and as a final step (*d*) we replace selected rigid links from the added links by *variable length links* such that we get the final underactuated mechanism that satisfies all design requirements. Here more comments regarding each step:

1) Initial fully-actuated open-chain linkage: Let us consider the desired trajectories of digits. Fig. 2*a* and 3*a* show the bending sequence for the initial open-chain linkages of the index finger and thumb, respectively. Both digits are equipped with two phalanges A_1B and BH, and two revolute joints A_1 and B. Fig. 2*a* indicates rotation of the index finger around the hand's palm, while Fig. 3*a* indicates thumb motion for parallel grip. Generally, two motors located in joints are needed to control each finger. At this stage, we need to fix trajectories and lengths of the digits' phalanges.

2) Motors' relocation: Motors can be remarkably bulky such as they significantly affect the mechanism's inertia or even cannot be installed in the joints. We propose a solution to extend the open-chain linkage by adding *groups* of rigid links to relocate actuators near to the hand's palm.

Since the index finger and the thumb have the same topology in our example, according to the design procedure [7], we need to add a group of links indicated by $h_{n,P} = h_{2,3}$ that consists of two links $n_a = 2$ and three revolute joints $P_{5_a} = 3$. Indeed, according to the Chebychev–Grübler–Kutzbach criterion for planar mechanism, the adding group has zero degrees of freedom W_a (DoF) and do not affects fingers' DoF

$$W_a = 3n_a - 2P_{5_a} = 0.$$

Fig. 2*b* and 3*b* show the digits linkages with added groups of links $h_{2,3}$ that consists of two green links CD and DA and three revolute joints A_2, D, and C.

The added groups of links must not affect the fingers' trajectories. Thus, we need to set an optimization task to find the links' lengths l_{CD} and l_{A_2D}, and locations where they need to be attached such that the initial trajectories are preserved. For both two-phalanges fingers, we seek the mentioned group's parameters such that the desired and current trajectories vary least throughout the motion. The mean squared world-space distance between the desired and current positions for two extreme points of distal phalanx B and H is given by

$$f = \sqrt{||p_H - p_H^*||^2 + ||p_B - p_B^*||^2},$$

is treated as a cost function for optimization where $p_H* = f(x_H, y_H, \phi_H)$ and $p_B* = f(x_B, y_B, \phi_B)$ are the sets of the desired trajectories for extreme points H and B respectively, $p_H = f(l_{CD}, l_{A_2D}, p_C, p_{A_2})$ and $p_B = f(l_{CD}, l_{A_2D}, p_C, p_{A_2})$ are the sets of the current trajectories for extreme points H and B which depends on parameters of the added group of links. The produced linkages also have 2 DoF just like the initial open chains mechanisms, but the motors can be installed near to the hand's palm, e.g., at the joints A_1 and D.

Here and further, we used MATLAB's Simscape Multibody and Global Optimization Toolbox with *patternsearch* function to conduct the optimization task.

3) Motors' elimination: To eliminate motors, we again have to add a group of links to bring holonomic constraints. According to the design procedure [7], we need to add the group $h_{1,2}$ or $h_{3,5}$. Here we consider both cases: we add the group $h_{1,2}$ that consists of one link $n_a = 1$ with two revolute joints $P_{5_a} = 2$ to the index finger and the group $h_{3,5}$ of three links $n_a = 3$ with five revolute joints $P_{5_a} = 5$ to the thumb mechanism. Indeed, according to the Chebychev–Grübler–Kutzbach criterion for planar mechanism, the adding group has negative DoF W_a and decrease fingers' DoF. For example for the index finger we have

$$W_a = 3n_a - 2P_{5_a} = 3 \cdot 1 - 2 \cdot 2 = -1.$$

Just like at the previous stage, we need to optimize the links' lengths of a new group to be added and find locations where it has to be attached. The intuition of the approach is similar to [11]: if the distance d between two points on a pair of components is constant over an entire motion cycle, then these components can be connected through a rigid link $h_{1,2}$ with distance d or further groups of links such as $h_{3,5}$.

For two different links i and j we seek a pair of points q_i and q_j whose world-space distance vary least throughout the motion. The mean squared world-space distance between the these two points is given by

$$l_{ij} = \frac{1}{n}\sum_{i}^{n} ||p_i(t_i) - p_j(t_i)||^2,$$

where n is the number of discrete time samples that span the entire motion cycle. To find the group parameters we need to set the optimization task with the following cost function

$$f = \frac{1}{n}\sum_{i}^{n}(||p_i(t_i) - p_j(t_i)||^2 - l_{ij})^2.$$

Fig. 2*c* and Fig. 3*c* show the linkages with added groups of links that eliminate one motor. The added groups $h_{1,2}$ and $h_{3,5}$ are painted in blue. The index finger has been augmented with one link EF, while the thumb has been augmented with three links: binary EF, ternary FGI, and binary IJ. Both mentioned linkages need only one motor for actuation. The red dot indicates motor, while the black dots indicate passive joints.

4) Underactuation introduction: The synthesized linkages are able to follow the desired trajectories. However, if physical contacts take place, the linkages are going to be stuck since they are not adaptive. To overcome this limitation we suggest to replace one or several rigid links added at the previous stages by a *passive variable length link* (PVLL). By doing so we embed mechanical compliance and make system responsive to external forces.

The links painted in red in Fig. 2*d* and 3*d* indicate PVLL. PVLL is an elastic body or and assembly of two rigid bodies connected via a spring-loaded prismatic joint. Lengths of PVLL change because of holonomic constraints and applied external forces. The integration of PVLL makes mechanisms underactuated.

The synthesized underactuated mechanism with PVLL still can follow the desired trajectories. Fig. 2*e* shows the index finger's rotation. In addition to that, the linkages can mechanically adapt to objects' shapes. Fig. 2*f-h* and 3*e-g* show interaction of digits with external objects. Here the essential feature is the *equilibrium line* that divide the distal phalanges on two areas: pinch area and encompassing area. The pinch grasp occurs when load is applied above the equilibrium line (Fig. 2*f*, Fig. 3*d*), while the encompassing grasp occurs when load is applied below the equilibrium line (Fig. 2*g*, Fig. 3*e*) [12]. The PVLL keeps its length if the load is applied above the equilibrium line (Fig. 2*f*, Fig. 3*d*) and gets variable if it is applied below (Fig. 2*g*, Fig. 3*e*). Furthermore, if proximal phalanx interacts with an object, it leads to encompassing grip (Fig. 3*f*). Figures 2*h* and 3*g* show the digits performing an adaptive grasp of a sphere.

Thus, we conducted the *structural-parametric synthesis* of planar closed-chain linkages for robotic applications that:(*a*) relocates actuators to a mechanism's base to decrease linkage inertia, (*b*) reduces the number of actuators by holonomic constraints, (*c*) introduces mechanical compliance to act stably under physical interactions. The synthesized mechanisms (*i*) can be driven by a few actuators with simple position control algorithms, (*ii*) physically interact with the environment, and (*iii*) can be reconfigured between 'precise tracking' and 'compliant interaction' modes. If there is no physical interaction, the synthesized mechanism follows a predefined trajectory and automatically adjusts in response to external forces in case of interaction.

III. HAND'S DESIGN

The synthesized linkages are a 'half-stuff' result. Another challenge is to develop a compact light anthropomorphic hand design with five more robust and functional digits that can lift heavier objects than a similar size and mass tendon-driven artificial hand. The RUA gripper is designed for the iCub humanoid robot-child. The primary condition is that the

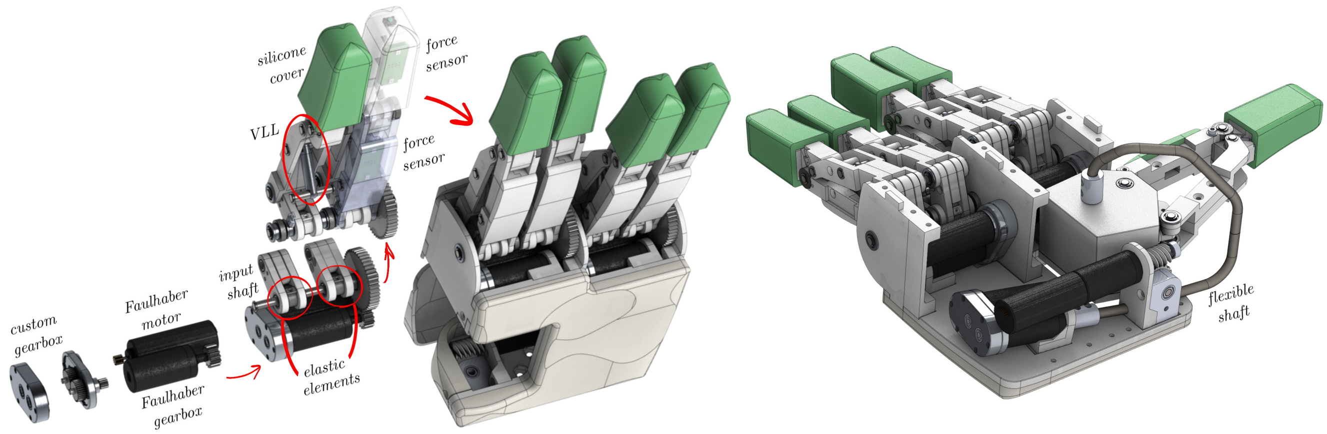

Fig. 4. Exploded view render of the RUA Gripper to highlight the main design features

gripper mechanically and electrically has to be attachable to the iCub robot, it has to be within the same sizes and mass, and the payload must be at least 1 *kg*.

The original iCub gripper is an underactuated tendon-driven one. Like most tendon-driven grippers, one can perform many gestures and perform encompassing grasps; however, the underactuated tendon-driven gripper's main drawback is a lack of precision and payload. It is not possible to achieve a secure pinch grasp of tiny objects and because of tiny DC motors and a back-drivable pulley system, the original gripper's payload is bounded to 350 g [13]. Also, the accuracy is limited because of elasticity and tension in cables [9], [13], [14].

The RUA Gripper has five active digits, but it needs only four motors for steering. Let us dive into the details concerning the gripper design. The Fig. 4 shows the exploded view render of the RUA Gripper to highlight the main design features. Fig. 5 gives detailed schematic representation of digits' actuation. Here are elaborated comments regarding each feature:

1) Custom gearbox: The Faulhaber Series 1224 DC motor with a rated torque of 1.7 *mNm* and a rated speed of 8580 min^{-1} has been chosen to actuate the digits. To increase the torque, the Faulhaber Series 12/4 planetary gearbox with gear ratio 64:1 has been taken. Apart from the *torque characteristics*, the essential criterion for the chosen DC motor and the gearbox is their *tiny dimensions*, i.e., ⌀ 12 *mm*, and the lengths are 38.2 *mm* and 34.3 *mm* respectively.

However, to securely lift a load weighing 1 *kg*, a drive has to generate approximately 1 *Nm* of torque, and the performance of the chosen planetary gearbox is not enough. Furthermore, the motor-gearbox assembly is 55.6 *mm* long, which does not fit into the requirements of compact sizes. To overcome the mentioned limitation, we installed the *Faulhaber motor* (Fig. 4) parallel to the *Faulhaber gearbox* and designed a *custom gearbox* to transmit the motion from the Faulhaber motor to the Faulhaber gearbox. The gear ratio of the custom gearbox is 2.5:1. Gears and gearbox's body are made from steel 1045 and M1017 respectively. To get an idea of the scale, here the smallest gear's pitch diameter is 3 *mm* and its modulus is 0.25.

2) Torsion elastic elements: The motion transmits further to the spur gear with a gear ratio of 3:1. A small input spur gear is fixed with a shaft of the Faulhaber gearbox, while a bigger output spur gear is fixed with fingers' *input shaft*. Index and middle fingers have a shared *input shaft* such that a single actuator is used. To prevent fingers from getting stuck during adaptive grasp, fingers' *inputs links* are attached to the *input shaft* through *torsion elastic elements*. Spur gears and shafts are made from steel 1045, while the elastic elements are printed from polyurethane.

3) Actuation: The gripper is equipped with four drives. The first drive actuates both index and middle fingers, and the second drive actuates the ring and little fingers since they also share the same input shaft. The third and the fourth go to the thumb: one for the thumb's flexion/extension and the another for abduction/adduction. Each digit linkage has 2 DoF, and furthermore, torsion elastic elements bring extra underactuation. Thus, the index-middle finger submodule has

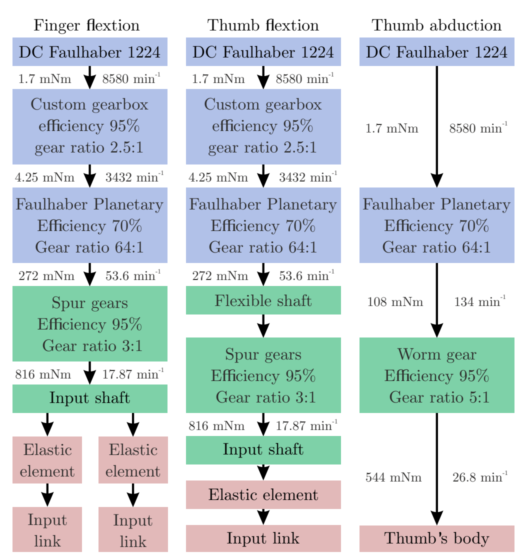

Fig. 5. Motion transformation from motors to digits' input links

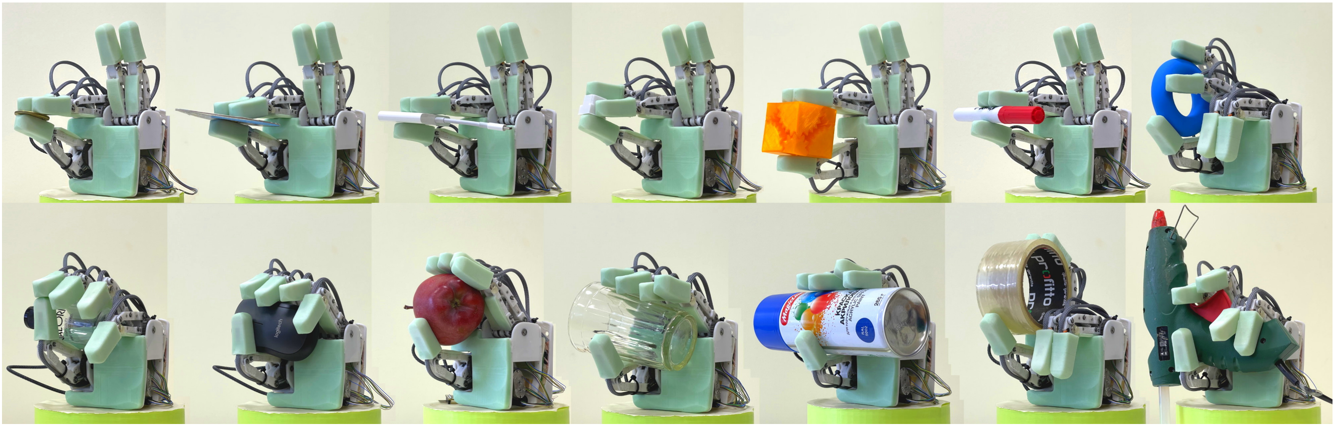

Fig. 6. The physical prototype of the RUA gripper is performing precision pinch and power encompassing grasps of random objects: a coin, a coaster, an adaptor, a tiny plastic part, a cube, a marker, an elastic torus, a bottle, a PC mouse, an apple, a glass, a spray paint, a duct tape, and a glue gun

5 DoF, 5 DoF for the ring-little finger submodel, 3 DoF for the thumb linkage with elastic element, and one more DoF for thumb abduction/adduction. The entire hand has 14 DoF.

The right image in Fig. 4 shows the gripper without a back cover to show where the drives are located. For thumb's flexion/extension motion from the drive is transmits through a flexible shaft. Such shafts are used for grinder hand tools. The flexible shaft since the drive is fixed to the hand's palm, while the thumb rotates around it. For thumb's abduction/adduction the Faulhaber motor is directly attached to the Faulhaber gearbox.

Fig. 5 gives an explicit representation of motion transformation from motors to digits' input links. Taking into consideration gears' efficiency each submodule generates 0.816 *Nm*, i.e., 2.448 *Nm* of torque in total.

4) PVLL and other features: Fig. 4 shows a passive variable length link (PVLL) under the hidden proximal phalanx of index finger. It consists of two metal bodies connected via a spring-loaded cylindrical joint. The parts of PVLL have been manufactured using CNC lathe.

IV. Physical Prototype

The RUA Gripper is designed to be installed on the iCub humanoid robot-child belonging to the Sber Robotics Lab. The primary condition is that the gripper *mechanically* and *electrically* has to be attachable to the iCub robot to ensure effortless integration into the robot architecture. This section reveals details concerning the gripper hardware, control algorithms, manufactured physical prototype, and demonstrates its grasping performance.

A. Hardware

To satisfy the integration with iCub robot, most of the components are inspired by the original iCub elements. Since not all iCub's parts are publically available, all the components have been manufactured based on open-source resources, e.g., [15].

An analogue of the original iCub's MC4-Plus DC motor driver board has been used to control all four Faulhaber motors. The motor driver board is based on the STM32F407VGT6 microcontroller and utilizes a double full-bridge L6206 to set rotation direction. The motor driver requires 12 V power supply.

An SS495A1 analog Hall sensor used in the original iCub's design has been used to measure joints' angular positions for the RUA gripper. The Hall sensor detects a change in the magnetic field. Each phalanx is equipped with a pair of a Hall sensor and a round magnet to measure angular offset. The Hall sensor is fixed with a phalanx part, while a ring NdFeB N35 is fixed with the corresponding joint's metal shaft. This set allows detecting motion within a range of $0^\circ - 180^\circ$ with accuracy of 0.5°. Considering the index finger and thumbs mechanisms (Fig. 2 and Fig. 3) the Hall sensors are installed into the joints A_1 and B.

An analog of the original iCub's MAIS board is used to process the analog data from the Hall sensor. The board is based on a 16-bit DSPIC30F4013 microcontroller and is capable of processing up to 15 analog channels. CAN-bus is used to transmit digital data further to the control board.

To measure contact force Alps Alpine HSFPAR003A and HSFPAR303A force sensors have been used. Both sensors are depicted in Fig. 4 inside the transparent distal phalanx of the middle finger. Besides the distal phalanx, the force sensors are located in proximal phalanx and palm. Palm, distal and proximal phalanges are covered with soft silicone covers needed for high friction between hand and objects and to protect the force sensors. Those sensors covered with silicone able to measure up to 40*N* of force. ADS1261 analog to digital converter is used for signals' amplification and processing.

B. Algorithms

The digits' mechanisms are able to adapt the objects' shape mechanically; thus, there is no need for complex control algorithms. However, to conduct desired types of grasps or gestures we use hybrid velocity-position-force control. The intuition for our approach is based on the following control law

$$\omega(t) = \omega^* \frac{F^* - F(t)}{F^*},$$

where $\omega(t)$ and ω^* are current and desired angular velocities of finger's input link respectively, $F(t)$ and F^* are current and desired interaction force. As long as the force $F(t)$ is zero, the current and desired velocities must be the same

$$e = \omega(t) - \omega^* = 0,$$

where e is angular velocity error. If $F(t) > 0$ the current angular velocity decreases, until the force $F(t)$ reaches the desired value F^*. Thus, we use PID angular velocity control to get the desired interaction force.

Furthermore, we look for the limit angular position, such that we do not waste energy to apply force at the palm in case there is no object to grasp. Moreover, we have only one control input and four angular position outputs for the index-middle finger subsystem. To perform our control approach, we need the only position of the input shaft, while the other data are needed to reconstruct the shape of the object being gripped. The same is true for the ring-little subsystem.

C. Testing

The RUA gripper's fingers are designed to be manufactured out of aluminium 6061-T6 to get a light and robust structure. However, to check the design's correctness, we created a 'plastic' prototype before the aluminum version. The total mass of the physical 'plastic' prototype is 495 grams. We call it 'plastic' since all links have been thickened and 3d printed using PETG plastic, but all axes, shafts, bearings, gearboxes, and motors are metal. The plastic parts of the physical prototype are thicker than those of the aluminium version; the thinned aluminium version has to be within the same mass of 0.5 kg.

Fig. 6 shows the physical 'plastic' prototype of the RUA gripper, which is performing precision pinch and power encompassing grasps of random objects found in the lab. Due to the synthesised linkages the hand is able to grasp all the objects. Here we want to highlight that all digits adapt to the shape of a grasped object, not just the one which touches an object first due to the torsion elastic elements. The heaviest object that has been tested is a 370 g paint spray. Although the calculated payload is 1 kg, it is pointless to check the payload of a plastic version because of significantly different yield strength of PETG plastic and 6061-T6 aluminium. Nevertheless, the calculated payload was confirmed by simulation in MATLAB Simscape Multibody.

V. CONCLUSIONS

Our contribution is an design approach that allows to achieve morphological computation of control law for anthropomorphic robotic grippers. Here we proposed the design of a mechanically reconfigurable underactuated gripper with 14 DoF actuated by only four motors. We followed a physical intelligence concept transferring some of the control tasks to mechanics. Thanks to the closed-chain linkages, variable-length links, and flexible elements, the gripper mechanically adapts to the shape of objects without any complex control algorithms.

As for the physical prototype, we used the iCub robot's original electronics components as much as possible and made a similar control system such that the gripper can be integrated into the robot with minimal changes to the robot's architecture. The iCub is a cutting-edge platform widely used by the robotics community, particularly those involved in manipulation, grasping, cognition, and human-robot interaction research. We believe our contribution allows us to extend the range of the iCub's field applications since to original hand's low payload capacity of 350 g strongly limits the robot's application in object manipulation tasks, e.g., grasping a cup of tea is not possible.

In the following paper, we want to reveal what more sophisticated control strategies can be used to control such underactuated multi-finger hand and demonstrate integration with the iCub robot.

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