Robot hand design with linkage and push-pull cable transmission

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Abstract— **This paper presents the architecture of a new hand for the robot iCub. This new hand consists of five fingers actuated by five motors. The thumb is actuated both in flexion and in abduction, the index and the middle finger are actuated independently, and finally, the ring and the little finger are actuated together. The architecture of the finger combines a linkage-based approach and a cable actuation. The hand uses a push-pull cable system; only one cable does both extension and flexion of a finger. Moreover, the cable is connected to the motor thanks to a helical link. This allows the transmission of higher forces.**

I. Introduction

The increasing demands for physical interaction between humans and robots have led to the development of robots that guarantee safety during physical Human-Robot Interaction (pHRI). Two promising application areas for such cooperative robots are industrial environments and domestic environments. In both environments, robots must be able to operate objects [1] and cooperate with humans. To increase safety, all aspects of a given design (i.e. mechanics, electronics, and software) should be considered.

The safety principles for mechanical design are for example the elimination of sharp edges or the reduction of the weight in the moving parts of the robot but also the use of sensors for the estimation of the state of the robot as well as the perception of the external environment [2]. The work presented in this paper is an application of these principles to the design of the hand of a humanoid robot.

The hands of a robot play an important role [3], as they are the link between the robots and the environment. Humans environments are designed to be interacted with by humans. For this reason, it is very important for artificial systems to comply with human forms and dimensions. This consideration also holds for robotic hands intended to manipulate and operate with everyday objects, as explained by Bicchi in [4].

A robot in direct contact with humans must be able to interact with them; one method could be by gestures such as finger pointing, or handshaking. Therefore, to achieve this a robot should have a human-like hand, inspired by the anatomy and equipped with pressure sensors, as Melchiorri and Kaneko point out in [5].

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The tactile modality is crucial for manipulation tasks. As explained by Z.Kappassov et al [6], the robotic hand has a smaller contact surface than a human hand, this issue decreases the sensing area significantly and causes difficulties with the grasping. It is therefore very important to maximize the contact surfaces covered with tactile, To achieve this objective the architecture of the finger needs to be carefully considered. In fact, the amount of surface that can be endowed with sensors depends on the position of the center of the rotation of the inter-phalanx joint.

Among the architectures of humanoid fingers, two approaches are particularly interesting: tendon approach and linkage approach.

In the cable approach, a motor, often located in the forearm of the robot, actuates the finger thanks to one or two cables. This has the advantage of relocating the motor out of the hand main assembly. Therefore, the weight is moved to more proximal locations (e.g. the forearm) thus allowing safer movements. In addition, the space available for the motor is generally wider, so motors that are more powerful can be used. This solution is the one currently employed in the iCub robot [7]. Although as the cable is moving between the palmar surface and the center of rotation of the inter-phalanx joint, this reduces the contact surface highly, and the possibility of sensor skin.

The second approach (used for example in the Bebionics hand[8]), consists of a direct actuation thanks to gears or links. Contrary to the previous architecture the motors are located as close as possible to the link location, sometimes directly in the joint. The advantage of the linkage is the wide contact surface and the possibility of a skin sensor. Although, as the motors are located directly in the hand, space as well as the power are limited , and the weight in the extremity is increased.

The goal of the work presented in this paper is the creation of an alternative design for the current hand of the iCub with improved dependability and sensing capabilities. A previous work conducted by Sureshbabu et al. [9] attempted to reduce the number of components and the overall cost of the iCub hand. Yet the contact surface was too small for a proper sensorization of this surface. To avoid this problem, the new hand will develop a new architecture, combining both the linkage approach, to increase the contact surface, and the cable approach. The finger consists of a bar linkage, but it is actuated by a cable. Another novelty is the use of only one cable for both flexion and extension of the finger.

To achieve these objectives two architectures will be considered, the first one inspired by the work of Birglen et al. [10] consists of a three DoF finger, the second one inspired by the work of Controzzi et al. on the SSSA-MyHand [11], consists of a two DoF cross-bar mechanism.

II. Objectives

The iCub is a humanoid robot; it has the size of a three years old child [12]. The main objective of the work presented in this article is to develop an alternative hand design to replace one currently employed. The requirements for this new hand are the following in order of importance:

- human design,
- improved the sensitivity,
- improved robustness,
- improved repeatability,
- simple design.

All of these will be described in greater detail in the following sub-sections.

A. Human anatomy

The first condition is to respect the human aspect of the hand. A human finger consists of four phalanges: Distal, Medial, Proximal, and Metacarpal. The last one is in the palm of the hand. The muscles that actuate the fingers are located in the forearm, and they can move the finger with the help of tendons. The new hand should respect this human-like aspect.

B. Sensitivity

For the future hand of iCub, a rich suite of sensors, including angle encoders, tactile sensors, and accelerometers, will assure the sensitivity of the hand. The actual implementation of the sensing elements is closely linked to the position of the center of rotation (COR). Usually, the COR is in the middle of the finger as shown in Fig 1a. This implies a large loss of contact surface, with the subsequent loss of space for the tactile sensors. However, a COR location close to the palmar surface leads to a small loss in the contact surface, but implies a greater force to move the finger as shown in Fig.1b A possible solution to this problem is to swap the position of the COR and the cable. The cable is no more between the palmar surface and the COR but between the COR and the dorsal surface of the finger, as shown in the Fig 1c. Yet a problem subsists in this configuration; the cable cannot close the finger, as the cable will be pushed out of the interphalangeal joint during the closure movement. In fact, this solution is already used for an exoskeleton where the patient cannot open the hand [13]. The patient does the closing movement, and the exoskeleton is helping the open movement. To solve this issue, a solution is the use of link bar system, as shown in Fig 1d.

C. Robustness

The current hand implementation of the iCub is limited in robustness mainly because of its cable actuation. For each finger, two cables go through the entire finger and come back to the motor for the actuation of the movement. The connection of the cable to the driven link has proven to be problematic and failure-prone. To reduce this fragility, a solution is the use of only one cable. This cable will be linked to the motor thanks to a helicoidal connection. This system highly reduces the radial load and allows a higher transmission of force thus a bigger load for the hand.

D. Repeatability

The current iCub hand is equipped with an analog encoder to measure the angle of rotation of finger joints. The linearity of this encoder highly depends on the precision of the assembly procedure thus requiring great care in the calibration phase. The goal is to find a solution for a replacement for this sensor.

E. Simple design

The design should have a minimal number of parts; it should be also easily assembled and disassembled. The different parts of the hand should be also easily manufactured, either by 3D printing or by 2D laser or water-jet cutting in case of metal parts. The number of degrees of freedom (DOF) is reduced to five, two for the thumb, one for the index, one for the middle, and the last one for both the ring and the little finger. To minimize moving masses, motors are located in the forearm, to reduce the end-effector weight and decrease the inertial and gravitational loads on the hand.

III. Solution

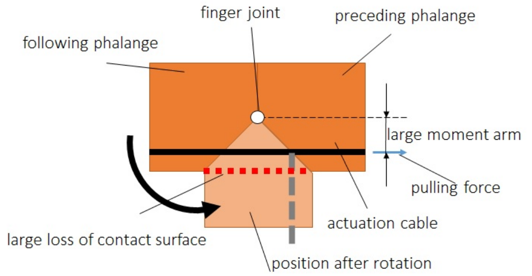
To achieve these requirements, two architectures for the finger were investigated. The first solution is inspired by the work of the University of Laval [14]; it consists of a 4-link finger and three DoF. The second solution is inspired by the work of Controzzi et al. for the H2020 DeTop research project [11]. It consists of a 3-link finger with two DoF. Fig 2 shows both these architectures. Both architectures have a COR, between the phalanges, close to the palmar face.

A. Architecture of the University of Laval

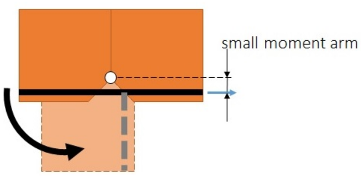
The finger consists of a link bar system composed of two successive quadrilaterals. The finger is actuated thanks to a crank system. The main advantage of this architecture is the respect of the human anatomy. In fact, the three phalanges are free and the three DoF are independent of each other. This last point can in some cases be considered a disadvantage because it implies that the finger needs to be equipped with several sensors to determine the position of the different phalanges. Another disadvantage is the length of displacement of the crank for the transmission of power. In this configuration, the length is around 30mm, which requires sacrificing a significant amount of volume. Finally, the architecture itself is complex with seven different pieces.

B. Architecture of myHand

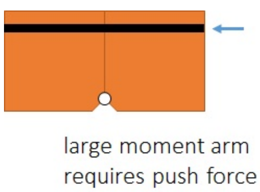
The finger consists of a crossbar system. The main difference with the previous system is the fusion of the two last phalanges. The finger is only actuated in the Metacarpal-Proximal joint and the Proximal-Medial joint. The main advantage of this architecture is its simplicity. In fact, it uses only four parts to actuate the finger contrary to the previous architecture. In addition, the metacarpal-proximal joint and



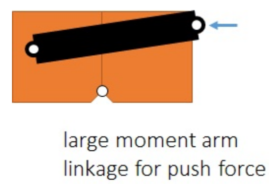
(a) Schema of the finger with a COR in the middle of the finger



(b) Schema of the finger with a COR closes to the palmar surface

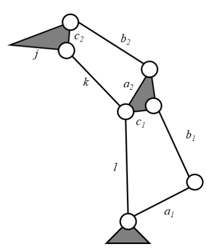


(c) Schema of the finger cable actuated

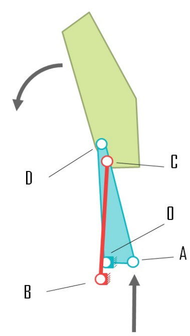


(d) Schema of the finger link bar actuated

Fig. 1: Schema of explanation of the position of the COR



(a) The Laval Architecture



(b) The DeTop architecture

Fig. 2: Both architectures investigated

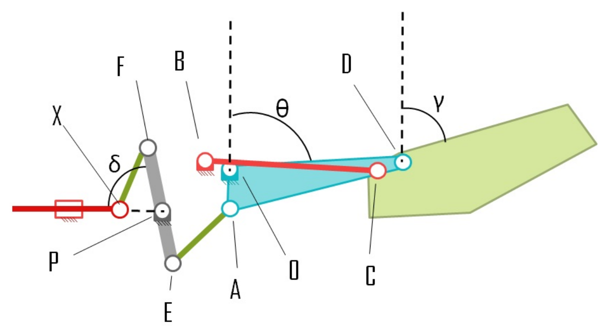


Fig. 3: Schema of the finger link bar actuated

the proximal-medial joint are related to the displacement of the crank. Therefore, only one sensor is needed to know the exact position of the finger. This increases the repeatability of the finger. As previous, the transmission of power is done by a crank system.

C. Dimension of the hand of iCub

The dimensions of the new hand inspired by the architecture of myHand are the dimension of the previous hand of iCub:

- Proximal phalange: 25mm
- Medial phalange: 20 mm
- Distal phalange: 15mm
- Angle of the Distal-Medial joint: 35°
- overall width: 12mm

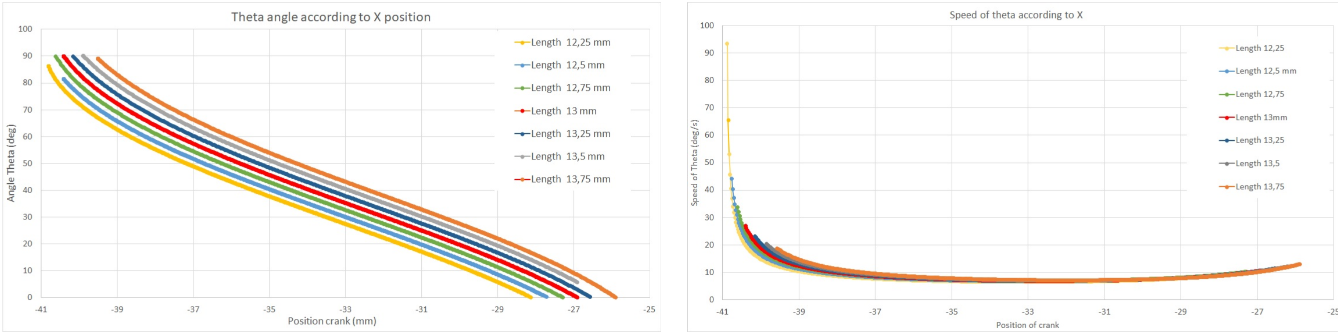
This gives us the length of the different part of the finger.

D. Push-Pull cable

As the hand size should be equivalent to the one of a three-year-old human hand, the space for the motors in the main hand body is limited. Therefore, the motors are located in the forearm of the robot. For the transmission of the movement between the motor and the finger, a cable used in push-pull configuration will be investigated. In this way, only one cable per motor is needed for achieving both the flexion and the extension movements. Previous implementations required instead either two cables or one cable and passive return systems like spring for every actuated DOF.

This new approach is inspired by the work of Danieli Telerobot Labs [13], who developed an exoskeleton of a hand. To help the extension of the hand, the motorization of this movement is only done during the extension. The flexion of the hand is done by the patient. The goal is to use this cable for both movements, the flexion and the extension.

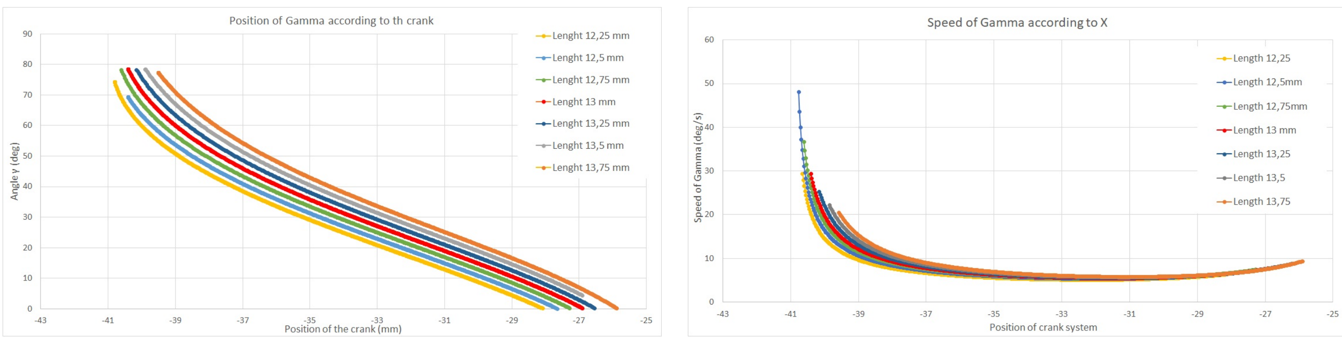
In the work of Danieli Telerobot Labs, pulling the cable results in the extension of the finger. For the hand of iCub, it



(a) The angle theta according to the crank position

(b) The speed of the angle theta according to the crank position

Fig. 4: Theta angle and his velocity



(a) The angle gamma according to the crank position

(b) The speed of the angle gamma according to the crank position

Fig. 5: Gamma angle and his velocity

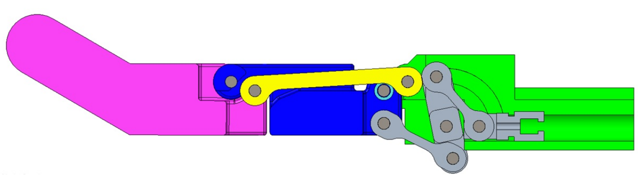


Fig. 6: Simulation of the finger link bar actuated

should be the inverse. Pulling the cable results in the flexion of the finger. In fact, the motor gives more power through the cable during the pull phase than the push phase.

To do this inversion, a system of a lever is used. This had the double function of inversion and power multiplier.

E. Parameters

As the lengths of the different bar are designed according to the length of iCub. The only length that can be modified is the crank bar that makes the link between the lever and the finger, the bar AE in the Fig 3. First, the length of this bar should be more than 12 mm. In fact, if it is smaller, there would be a singularity and the finger cannot close completely. Another limit is the maximum length of maximum 15 mm. If it is longer, the lever will also reach a singularity.

The parameter is the length of the bar, the criteria are:

- The displacement of the crank system: It should be between 10 and 15 mm.

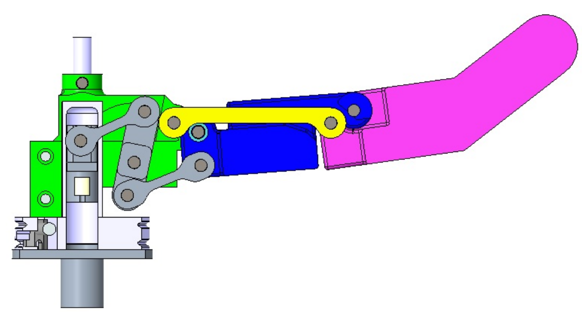
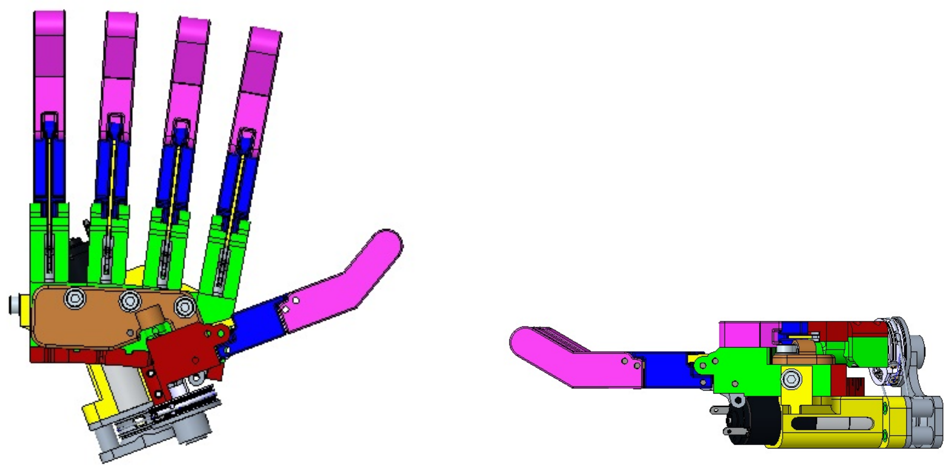


Fig. 7: Simulation of the thumb actuated

- The range of motion of the finger: The range of the angle shall be between 10°and 90°for the Metacarpal-Proximal Joint. And 5°and 80°for the Proximal-Medial Joint.
- The speed of closing of the finger: It should be less than 30°/s
- Due to the different singularities: the minimum angle of delta should be higher than 10°.

The Fig 4 and the Fig 5 show the angle of theta and gamma according to the position of the crank, and the speed of the angle theta and gamma according to the position of the crank.

The different figures and the table show the different criteria. As shown in the Fig 4b and in the Fig 5b the speed



(a) The palmar face of the hand (b) The side of the hand

Fig. 8: Simulation of the hand

TABLE I: Parameter according to different length

Length (mm)	Displacement (mm)	Range θ (°)	Range γ (°)	δ min (°)
12.25	12.8	0-90	0-78	3
12.5	13.3	0-90	0-78	7.42
12.75	13.06	2-90	1.5-78	11.2
13	12.75	5-90	4-78	14.8
13.25	12.71	7-90	5-78	18
13.5	12.32	10-90	7.5-78	21
13.75	12.1	12-90	9.5-78	24

of theta and gamma decrease when the length of the bar increase. One of the objectives is to have a safe hand closure; therefore, the speed shall be reasonable so less than 30°/s. To also avoid the singularity the angle of the crank shall always be superior to 10°.

With these criteria the lengths inferior to 13mm are eliminated, the other criterion is the biggest range of motion for the angle of the finger. Moreover, even if the length 13.25mm, 13.5 mm and 13.75 mm are slower and farther from the singularity position, the minimum angle of opening the finger disqualify them. In the end, the length of 13 mm, considering the criteria chosen, is the best choice for the finger. Fig 6 shows a computer-aided design (CAD) of the finger modeled on Creo Parametric 4.0.

F. Palm

The palm is composed of five fingers, except the thumb, all of them are based on the architecture showed previously. Concerning the thumb, the architecture is the same, except that the crank system is perpendicular to finger instead to be aligned. Fig 7 shows a computer-aided design (CAD) of the thumb modeled on Creo Parametric 4.0.

Two motors actuate the thumb, one is located in the palm, and the other is in the forearm. The motor in the palm does the abduction and adduction of the thumb. The other motor actuates the flexion and the extension of the thumb. A pulley cable system realizes the transmission of motion between the motor and the thumb to do the abduction and the adduction of the thumb. The Fig 8 shows a computer-aided design (CAD) of the hand, modeled on Creo Parametric 4.0.

IV. Future prototype

The Fig 9 shows the first prototype, It consists of a single finger. This finger will pass a fatigue test, to investigate the relatability. In the second phase, a full hand is manufactured.

A. Material

The main material for the hand is the plastic 3D printed. This allows for complex form and quick manufacturing. However, the rotational parts are made in bronze to avoid friction. In fact, the dimensions are too small for the use of a bearing, so the bronze material was selected. As most of the parts are flat, the process for the fabrication is the water cutting.

B. Motor

In the same idea of simplification and minimizing the cost, the motors are the same for every actuated DOF. The motor selected is DC-max16S GB KL 24V. The main features are the stall torque of 14mNm and a continuous torque of 4.87 mNm. This motor is coupled to a planetary gearhead: GPX16 A 103:1. The ratio is 103:1 and the maximum torque is 0.45Nm.

A screw transmission is used to transform the rotation movement of the motor in a translation movement that can push and pull the cable. This system has the advantage of suppressing the limit in the normal load and the torque. The main limitation of force applied on the finger is now in the tension of the cable. As the cable is 0.8 mm of diameter and support 500N of traction, a first study shows that the maximum force that can be applied to the extremity of the finger is 20N. Therefore, a finger can lift when closed a charge of 2kg, and a full hand in a hook position 8kg. This charge is limited by the other components of the robot such as the arm or the shoulder.

V. Conclusion

The proposed system is the result of an optimization of the mechanical design to meet all specifications in terms of dimension, robustness, ability, and power. Five motors, one located in the palm, the other in the forearm, actuate the final hand. Fives cables transmit the movement between the motors and the fingers; these cables are used in both extension and flexion, with the use of the push-pull system.

This new architecture reduces the loss in the contact surface of 40%, with the previous architecture the loss of surface was $140mm^2$, the new loss is only $86mm^2$.

Future work will focus on the integration of sensors to know the position, as well as, tactile sensor.

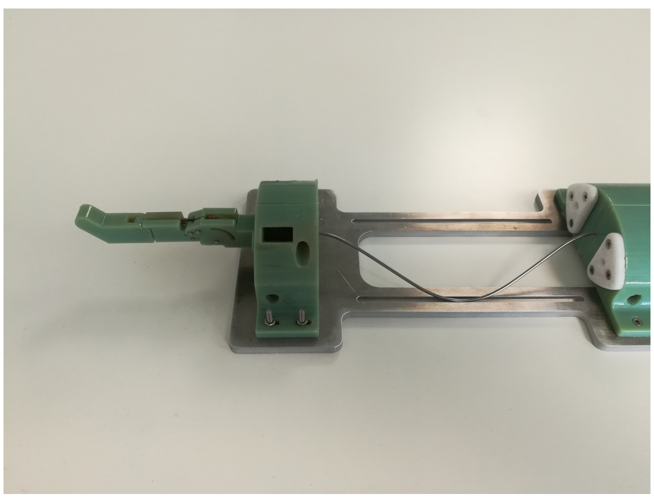


Fig. 9: Picture of the first finger protoype

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