PPMEC | Pós-Graduação em Sistemas Mecatrônicos
Faculdade de Tecnologia
Departamento de Engenharia Mecânica

Universidade de Brasília

Development of an Anthropomorphic Robotic Hand With Tactile Perception

Alberto J. Alvares

Artur Vitório Andrade Santos

alvares@AlvaresTech.com

Summary

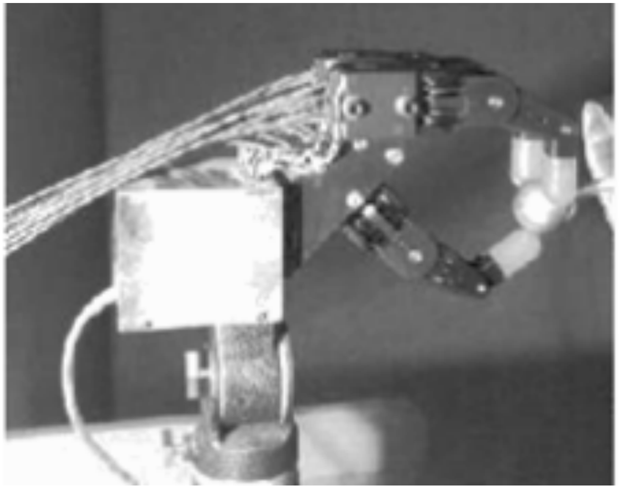
- Introduction: Anthropomorphic hands and Autonomous Manipulation (Underactuated Finger Using Tactile Sensor)
- Design methodology based on Quality Function Deployment (QFD)
- Modeling and kinematic analysis of the anthropomorphic hands
- Compliance Control
- Results, validation prototype and demonstrative video
- Conclusion

Anthropomorphic Hands

- Products produced more customizable
- Different types of robotic claws used
- Handle different categories of objects
- Integration of actuators, sensors and Controllers
- Underactuated hands
- Interest in the distribution of the forces
- Robotic hand refers to a particular type of end-effector with an anthropomorphic inspiration

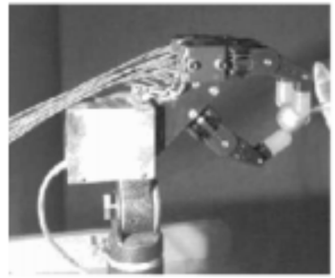
Autonomous Manipulation

- Domestic spaces are usually not structureed
- Unstable fingertipes are unable to maintain a stable grip
- Tactile sensors provide robots with physical contact information
- fully actuated mechanisms: ndof = nact;
- redundantly actuated mechanisms: ndof < nact;
- underactuated mechanisms: ndof > nact

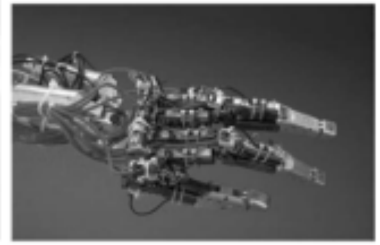


The number of DOF (ndof)
relatively to the number of actuators (nact)

(a) Bologna U. Hand (courtesy of Profs. G. Vassura and C. Melchiorri)

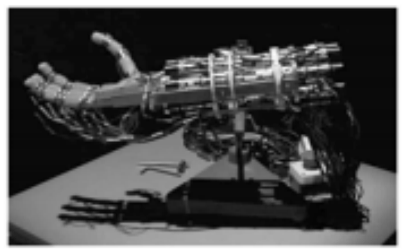


(b) Salisbury's Hand (courtesy of Prof. J.K. Salisbury)

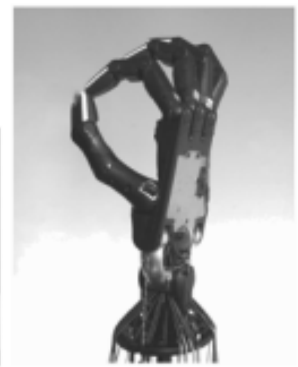


(c) Anthrobotics Omni-Hand (courtesy of M. Rosheim)

(d) Robonaut Hand (courtesy of NASA)



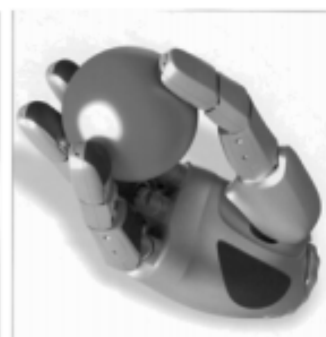
(e) LMS Hand (courtesy of Prof. J.P. Gazeau)



(f) Shadow C3 Hand (courtesy of R. Walker)

(g) DLR Hand I

(h) DLR Hand II



(i) HIT/DLR Hand

(pictures courtesy of Prof. G. Hirzinger)

Fig. 2.1. Anthropomorphic robotic hands

Comparison of different anthropomorphic hand

Robotic Hand	DOF	Actuador Number	Finger Number	Year	Actuator Type
Stanford/JPL	9	9	3	1983	Electric Motor (DC)
Utah/MIT	16	16	4	1985	Actuator Pneumatic
Belgrade/USC*	15	4	5	1988	Electric Motor (DC)
Barret*	8	4	3	1988	Brushless Motor
DLR I	12	12	4	1997	Electric
Dist	16	16	5	1998	Electric
Robonaut*	19	14	5	1999	Electric
DLR II	13	13	4	2001	Electric
Gifu*	20	16	5	1999	Micro Motor DC
RTR*	9	3	3	2001	Actuator Mckibben
Dexterous Robot*	16	5	4	2001	Electric Motor (DC)
Shadow	23	23	5	2002	Pneumatic
Speed Multifinger	10	10	3	2003	Electric
KNU*	16	2	5	2009	Electric Motor (DC)
ISR-Softhand*	10	3	5	2014	Dynamixel AX-12
SHU-II*	16	6	5	2016	Electric Motor (DC)
Pertuz*	16	7	5	2017	Electric Motor (DC)

* Obs: Underactuated Robotic Hand

Defined User Requirements (URs) or “What’s”

User requirements for anthropomorphic robotic hand

Stages of the Product Life Cycle	User Requirements
Functionality	To Handle objects of different shapes and sizes
	To have force feedback system with direct measurement
	To handle objects of different weights
	Manual and automatic finger control
	Being able to interact with the user
	Be compatible with robotic manipulators
	To have stability of movement of the fingers
Production	Low manufacture cost
	Products for assembly to be made accessible
	To have the appearance of the human hand
	Modular and easy to assemble
Usability	Accomplish force movements
	Accomplish precision movements
Consumption	Low power supply
Recycling	Use easily reusable materials

Mudge Diagram (A=5, B=3, C=1)

Mudge Diagram																	
Customer Requirements Number																	
-	2	3	4	5	6	7	8	9	10	11	12	13	14	15	SOMA	%	
1	2A	1A	1C	5A	6A	1B	8A	9C	10A	11B	12A	12A	14B	15C	9	3%	
	2	2A	2B	2B	6A	2B	2B	2C	10A	2C	12B	13B	2B	2B	30	10%	(3)
		3	4B	5B	6A	7B	8A	3B	10A	11B	12A	13A	3C	15C	4	1%	(7)
			4	5B	6A	4C	4A	4B	10A	4B	12C	13C	4C	15C	16	5%	
				5	6A	7B	5A	5B	5B	11B	5B	5B	5B	5C	29	9%	(4)
					6	7B	8B	9C	10C	11C	12C	13C	6A	6A	35	11%	(2)
						7	7A	7C	10C	7C	7C	7C	7B	7C	22	7%	
							8	9A	10C	11C	12C	13C	8B	15B	16	5%	
								9	10C	11C	12C	13C	14A	9C	8	3%	(5)
									10	10A	10C	10C	10A	10A	41	13%	(1)
										11	11A	11A	14B	11A	27	9%	
											12	12B	12A	12C	26	8%	
												13	13A	13C	23	7%	
													14	14A	16	5%	
														15	6	2%	(6)
														Total	308	100%	

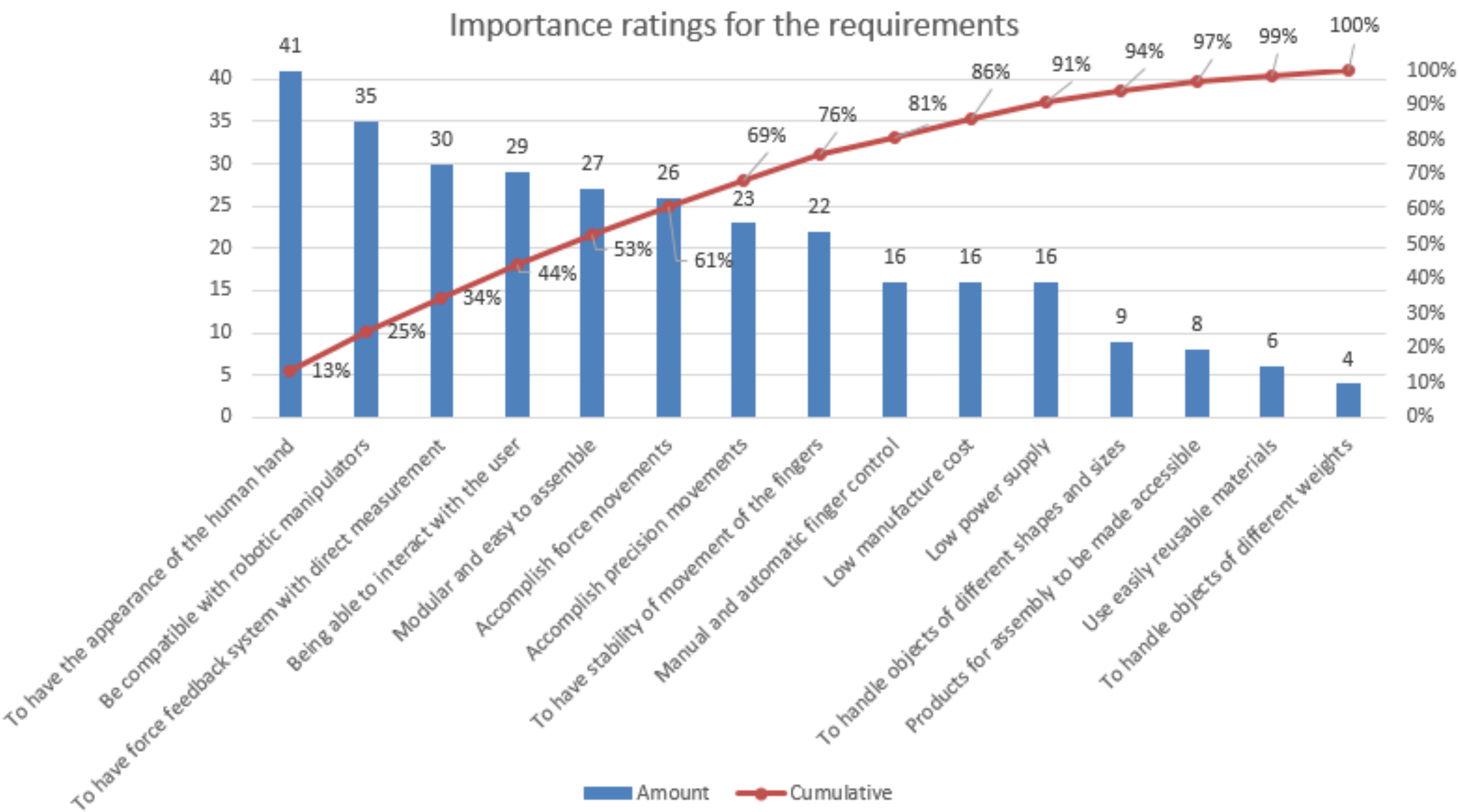
Priority Item:

- To have the appearance of the human hand (1)
- Be compatible with robotic manipulators (2)
- Force feedback system with direct measure (3)
- Being able to interact with the user (4)

Not Priority Item:

- Products for assembly to be made accessible (5)
- Uses easy reusable materials (6)
- To handle objects of different weight (7)

Average importance ratings for the user requirements shown in the Pareto chart



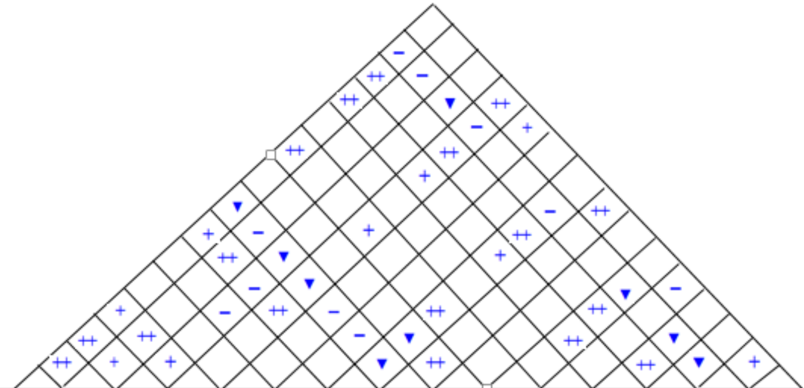
Selected Design Parameters (DPs) or "How's"

Table 3 – Product requirements for anthropomorphic robotic hand

Product Requirements	Trend	Unity
Number of fingers in the hands	Crescent	Unity
Force measuring sensor	Crescent	-
Max capacity of manipulation	Crescent	kg/cm
Compliance control	Crescent	-
Graphic interface	-	-
Fixation system	-	Unity
Control system accuracy	Crescent	-
Total cost of production	Decrescent	U$
Products found nationally	Crescent	-
Degree of freedom	Crescent	Unity
Possessing mounting modules	Decrescent	Unity
Forms of canonical force movement	Crescent	Unity
Canonical shapes of precision motion	Crescent	Unity
Power consumption	Decrescent	kW/h
Reprogrammable components Open-source	-	-

QFD – House of Quality

Legend		
⊙	Strong	5
○	Medium	3
▲	Weak	1
++	Strong Positive Correlation	-
+	Positive Correlation	-
—	Negative Correlation	-
▼	Strong Negative Correlation	-



Maximun Relationship	Relative Weight	User Importance	User Requirements \ Design Parameter	1.1 - Number of fingers in the hands	1.2 - Force measuring sensor	1.3 - Max capacity of manipulation	1.4 - Compliance control	1.5 - Graphic interface	1.6 - Fixation system	1.7 - Control system accuracy	2.1 - Total cost of production	2.2 - Products found nationally	2.3 - Degree of Freedom	2.4 - Possessing mounting modules	3.1 - Forms of canonical force movement	3.2 - Canonical shapes of precision motion	4.1 - Power consumption	4.2 - Reprogrammable Components (Open-source)
			Improvement	▲	▲	▲	X	X	X	▲	▼	▲	▲	▼	▲	▲	▼	X
5	7,0	9	To handle objects of different shapes and sizes	⊙	⊙	⊙	▲	▲		⊙	⊙		⊙	▲	⊙	⊙	○	▲
5	7,0	9	To have force feedback system with direct measurement	○	⊙	▲	⊙			⊙	○	▲					○	
5	7,0	9	To handle objects of different weights	○	⊙	○					⊙			▲			○	
5	6,2	8	Manual and automatic finger control	○			⊙	⊙		○	○							
5	6,2	8	Being able to interact with the user					⊙			○							
5	7,0	9	Be compatible with robotic manipulators						⊙		▲							
5	7,0	9	To have stability of movement of the fingers	▲			⊙			⊙	○						▲	
5	5,4	7	Low manufacture cost	⊙	⊙	⊙	⊙	⊙	○	⊙	⊙	⊙	⊙	○	○	○	⊙	⊙
5	7,0	9	Products for assembly to be made accessible		○	▲				▲	⊙	⊙						
5	7,0	9	To have the appearance of the human hand	⊙							○		⊙		⊙	⊙		
5	7,0	9	Modular and easy to assemble								⊙	⊙		⊙				○
5	7,0	9	Accomplish force movements	⊙	○	○				▲	⊙		⊙		⊙	▲	⊙	
5	7,0	9	Accomplish precision movements	⊙	⊙	○	⊙			⊙	⊙		⊙		▲	⊙	○	
5	5,4	7	Low power supply	⊙	⊙	⊙		▲		⊙	⊙		○				⊙	
5	7,0	9	Use easily reusable materials								⊙							⊙
			Target	5	Direct Measure	2 Kg/cm	Fuzzy Logic	Python	Flange	95%	R$ 500	-	Equal or Bigger than 15	-	Equal or Bigger than 4	Equal or Bigger than 4	Less than 500W	Hardware Open-Source
			Maximun Relationship	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
			Technical Rating Importance	261,2	235,7	165,9	169,8	101,6	51,16	226,4	405,4	103,9	182,9	65,12	127,9	127,9	179,8	89,92
			Relative Weight	10,5	9,4	6,7	6,8	4,1	2,1	9,1	16,3	4,2	7,3	2,6	5,1	5,1	7,2	3,6

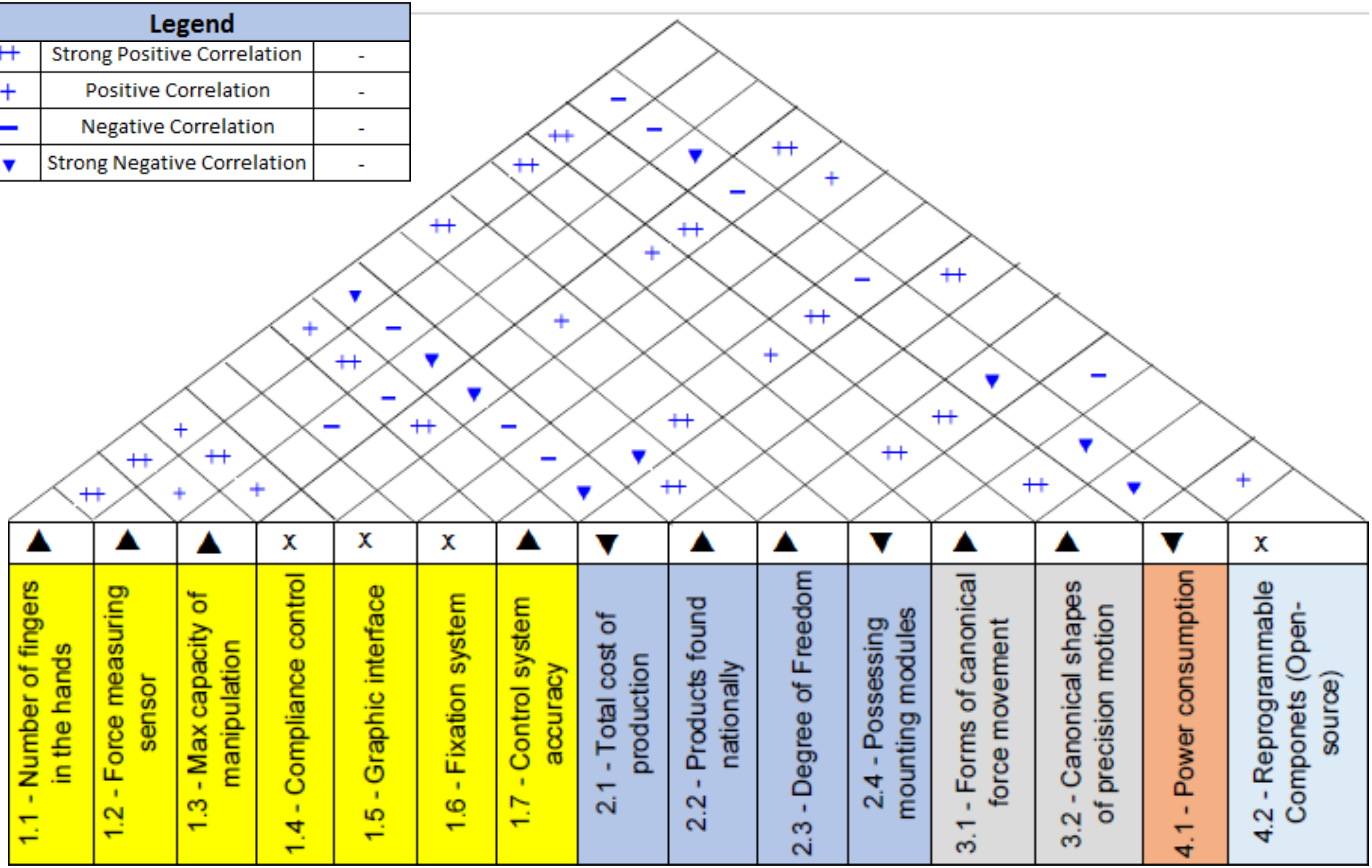
QFD matrix of relationship between RUs and DPs

Legend		
⊙	Strong	5
○	Medium	3
▲	Weak	1

User Requirements / Design Parameter	1.1 - Number of fingers in the hands	1.2 - Force measuring sensor	1.3 - Max capacity of manipulation	1.4 - Compliance control	1.5 - Graphic interface	1.6 - Fixation system	1.7 - Control system accuracy	2.1 - Total cost of production	2.2 - Products found nationally	2.3 - Degree of Freedom	2.4 - Possessing mounting modules	3.1 - Forms of canonical force movement	3.2 - Canonical shapes of precision motion	4.1 - Power consumption	4.2 - Reprogrammable Componets (Open-source)
Improvement	▲	▲	▲	x	x	x	▲	▼	▲	▲	▼	▲	▲	▼	x
To handle objects of different shapes and sizes	⊙	⊙	⊙	▲	▲		⊙	⊙		⊙	▲	⊙	⊙	○	▲
To have force feedback system with direct measurement	○	⊙	▲	⊙			⊙	○	▲					○	
To handle objects of different weights	○	⊙	○					⊙			▲			○	
Manual and automatic finger control	○			⊙	⊙		○	○							
Being able to interact with the user					⊙			○							
Be compatible with robotic manipulators						⊙		▲							
To have stability of movement of the fingers	▲			⊙			⊙	○						▲	
Low manufacture cost	⊙	⊙	⊙	⊙	⊙	○	⊙	⊙	⊙	⊙	○	○	○	⊙	⊙
Products for assembly to be made accessible		○	▲				▲	⊙	⊙						
To have the appearance of the human hand	⊙							○		⊙		⊙	⊙		
Modular and easy to assemble								⊙	⊙		⊙				○
Accomplish force movements	⊙	○	○				▲	⊙		⊙		⊙	▲	⊙	
Accomplish precision movements	⊙	⊙	○	⊙			⊙	⊙		⊙		▲	⊙	○	
Low power supply	⊙	⊙	⊙		▲		⊙	⊙		○				⊙	
Use easily reusable materials								⊙							⊙

Matrix of correlations between DPs

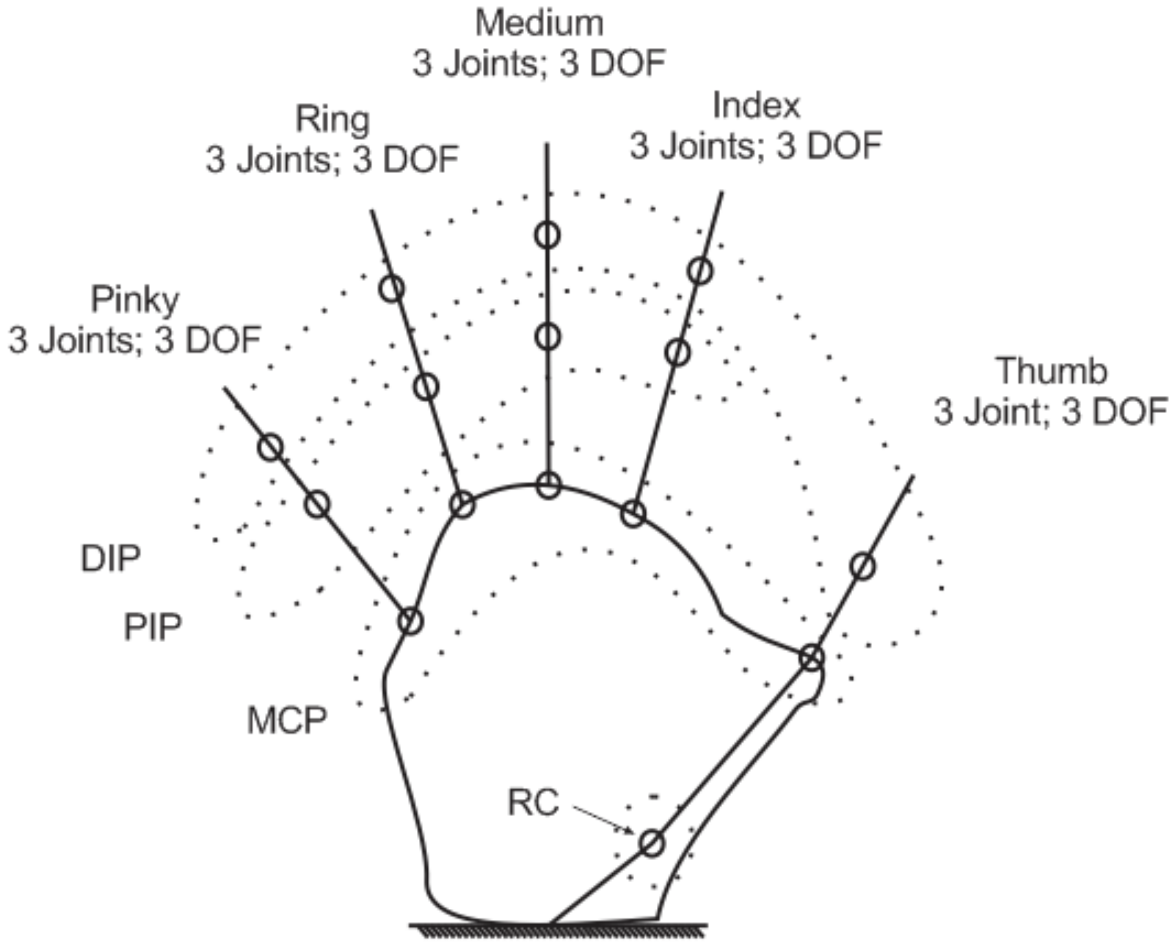
Legend		
++	Strong Positive Correlation	-
+	Positive Correlation	-
—	Negative Correlation	-
▼	Strong Negative Correlation	-



Specifications-meta for the anthropomorphic hand

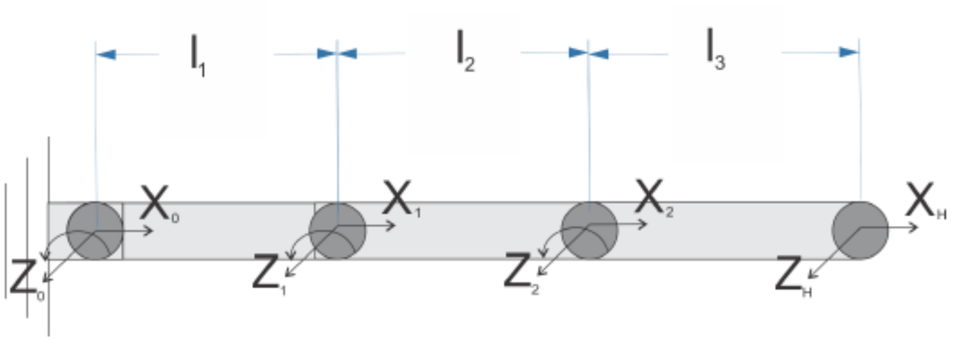
Relative Weight	Technical Rating Importance	Maximun Relationship	Target	
10,5	261,2	5	5	1.1 - Number of fingers in the hands
9,4	235,7	5	Direct Measure	1.2 - Force measuring sensor
6,7	166	5	2 Kg/cm	1.3 - Max capacity of manipulation
6,8	170	5	Fuzzy Logic	1.4 - Compliance control
4,1	101,6	5	Python	1.5 - Graphic interface
2,1	51,2	5	Flange	1.6 - Fixation system
9,1	226,4	5	95%	1.7 - Control system accuracy
16,3	405,4	5	R$ 500	2.1 - Total cost of production
4,2	103,9	5	-	2.2 - Products found nationally
7,3	182,9	5	Equal or Bigger than 15	2.3 - Degree of Freedom
2,6	65,12	5	-	2.4 - Possessing mounting modules
5,1	127,91	5	Equal or Bigger than 4	3.1 - Forms of canonical force movement
5,1	127,91	5	Equal or Bigger than 4	3.2 - Canonical shapes of precision motion
7,2	179,8	5	Less than 500W	4.1 - Power consumption
3,6	89,92	5	Hardware Open-Source	4.2 - Reprogrammable Componets (Open-source)

DOF representatiton



Kinematics model – Direct Kinematics

Direct kinematics for the pinky, ring, middle and index finger

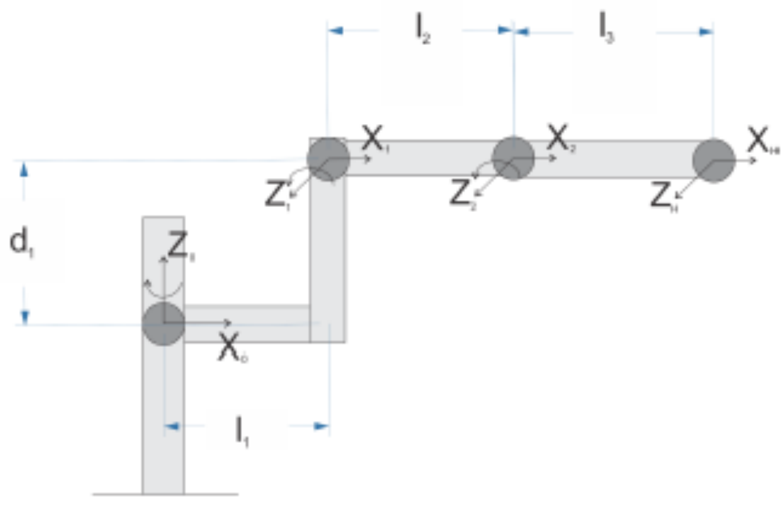


Joints	θ	α	l	d
MCP	θ_1	0	l_1	0
PIP	θ_2	0	l_2	0
DIP	θ_3	0	l_3	0

$$T_0^3 = \begin{bmatrix} c_{123} & -s_{123} & 0 & l_1c_1 + l_2c_{12} + l_3c_{123} \\ s_{123} & c_{123} & 0 & l_1s_1 + l_2s_{12} + l_3s_{123} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Kinematics model – Direct Kinematics

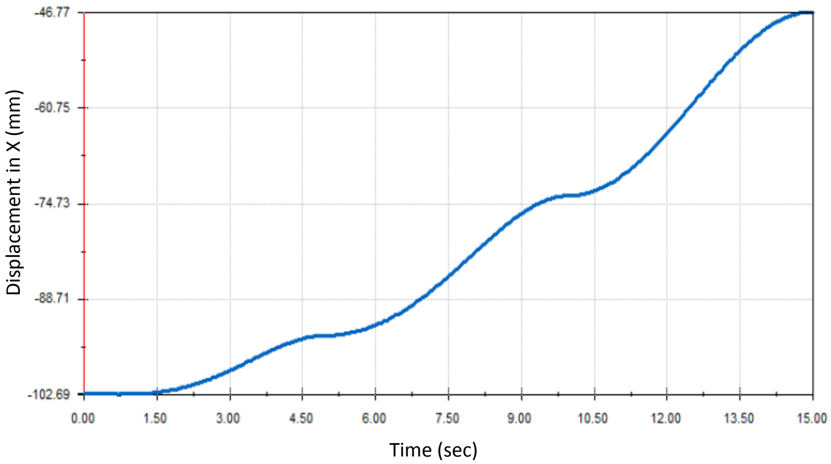
Direct kinematics for the thumb

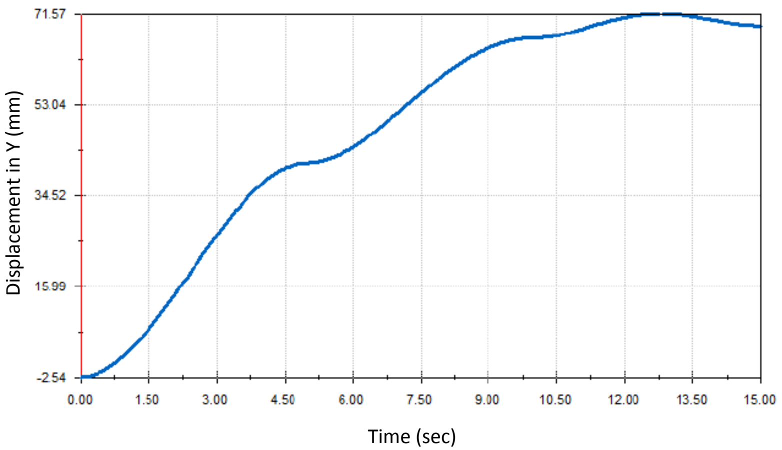


Joints	θ	α	l	d
RC	θ_1	90	l_1	d_1
MCP	θ_2	0	l_2	0
DIP	θ_3	0	l_3	0

$$T_0^3 = \begin{bmatrix} c_{23}.c_1 & -s_{23}.c_1 & s_1 & c_1(l_1 + l_3c_{23} + l_2c_2) \\ c_{23}.s_1 & -s_{23}.s_1 & -c_1 & s_1.(l_1 + l_3.c_{23} + l_2c_2) \\ s_{23} & c_{23} & 0 & d_1 + l_3.s_{23} + l_2.s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Results of Kinematics Analysis





COMPARISON OF CALCULATED AND MEASURED KINEMATICS

Values	MCP, DIP, PIP	X	Y	Z
Matlab	25, 30, 60	46.31 mm	71.58 mm	0 mm
SolidWorks	25, 30, 60	48.15 mm	71.07 mm	0 mm
Error	25, 30, 60	1.84 mm	0.51 mm	0 mm

Project Overview

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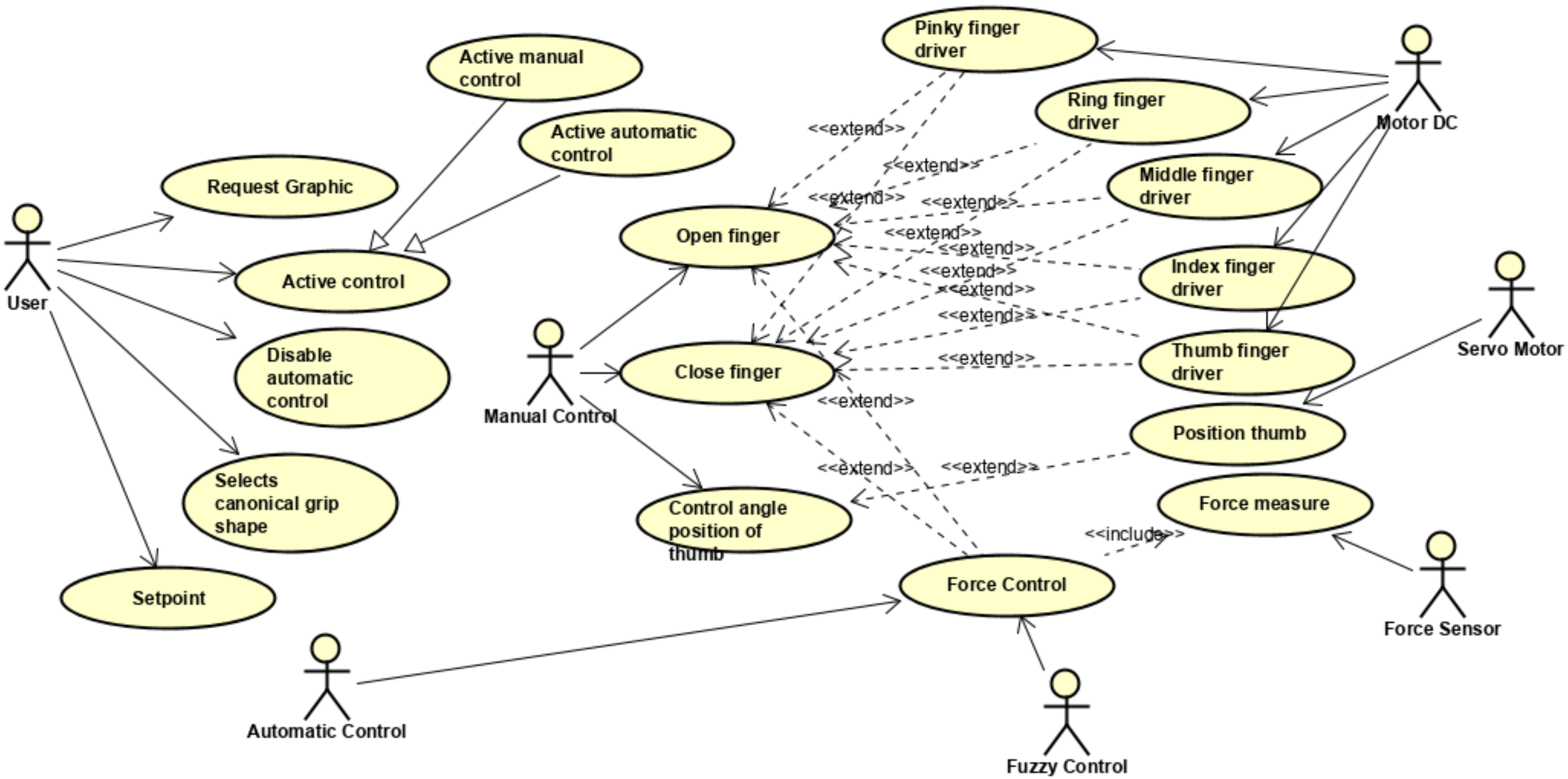
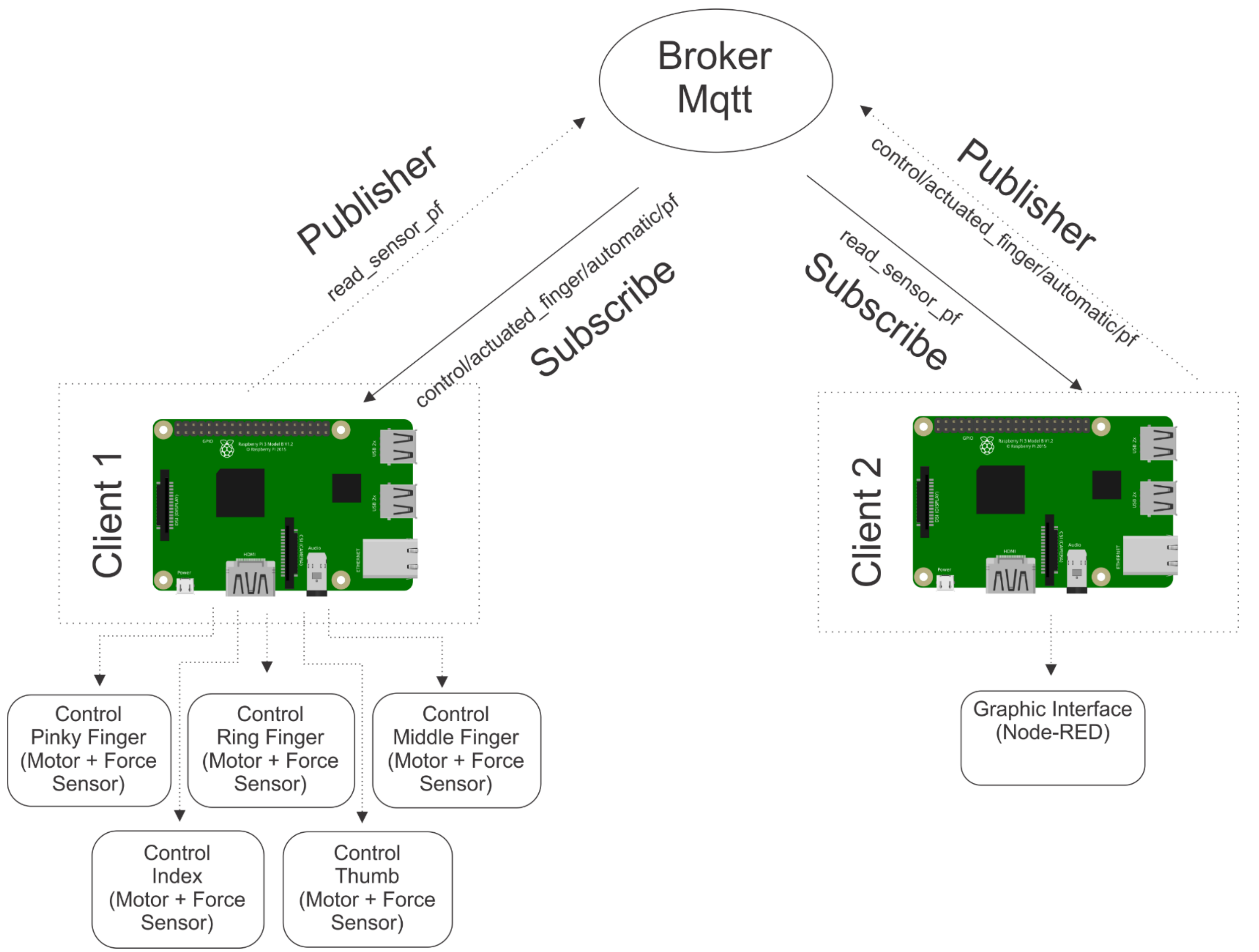
Use Case Diagram

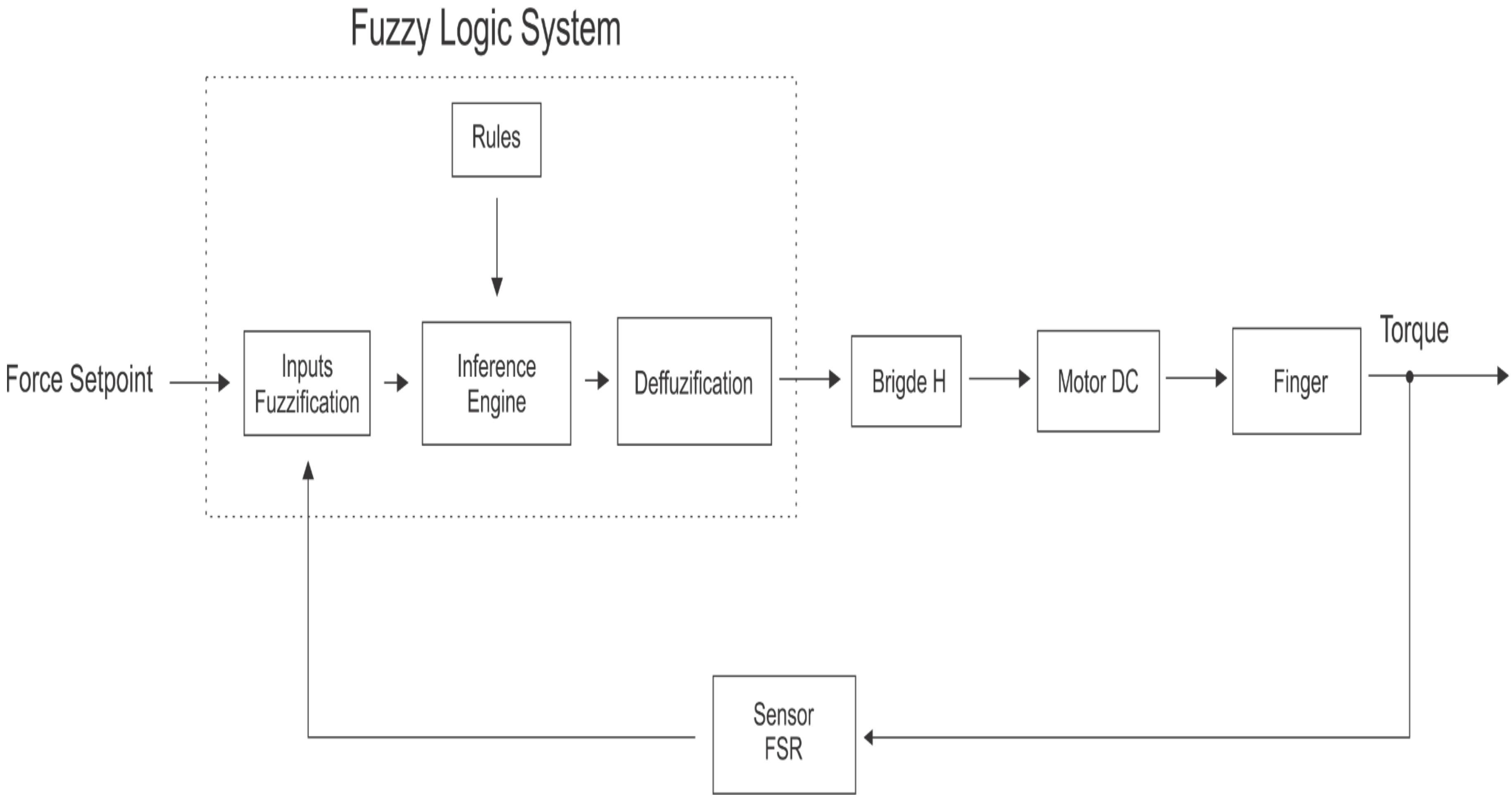


Communication Between Raspberrys Pi

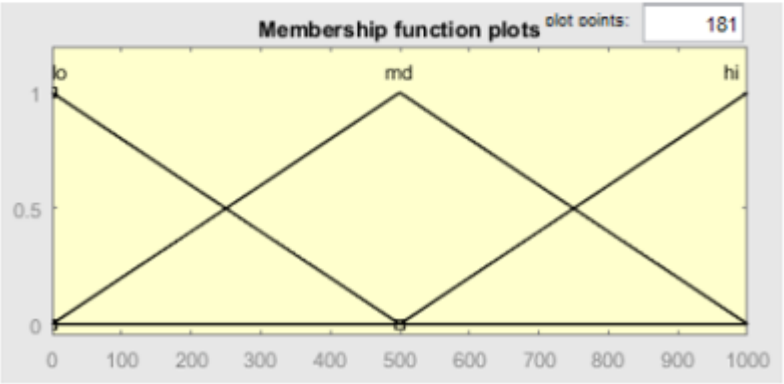
MQTT – Message Queuing Telemetry Transport

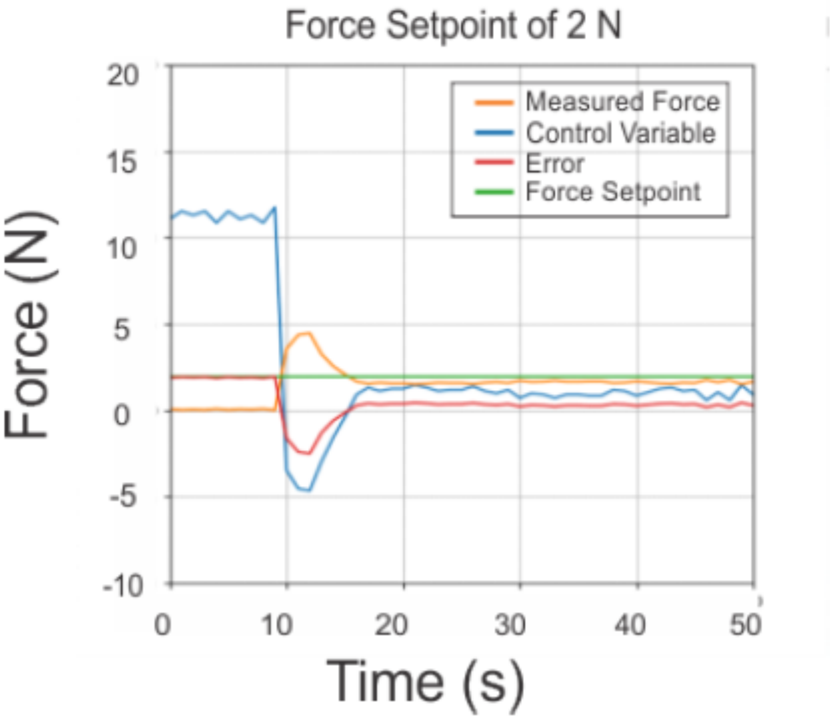


Compliance Control



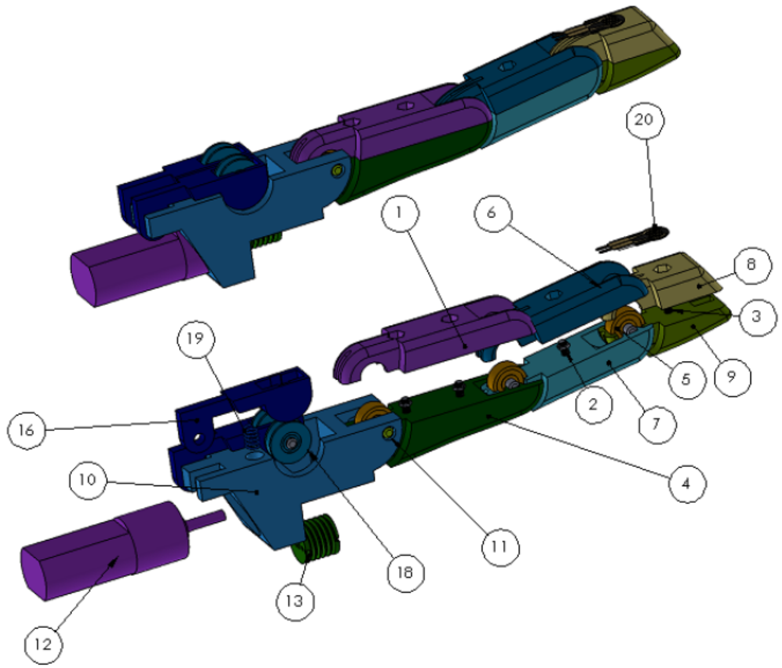
Compliance Control

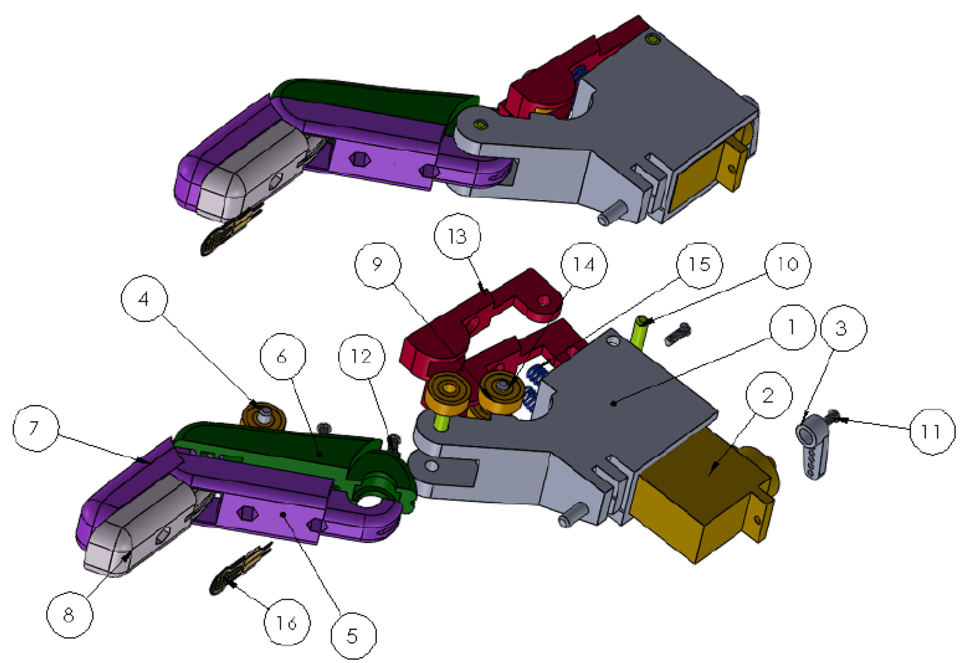




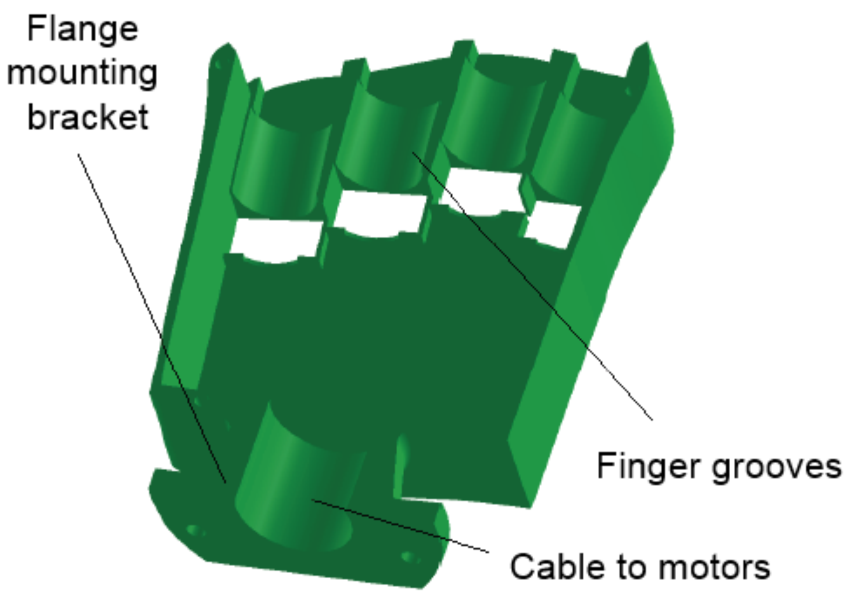
Force	Force Setpoint		
	Low	Normal	High
Low	Not Change	High	High
Normal	Low	Not Change	High
High	Low	Low	Not Change

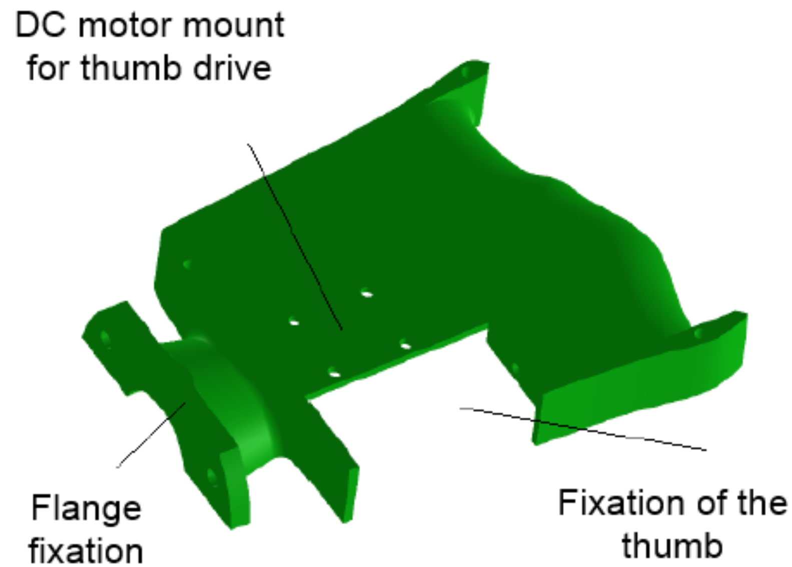
Detailing of fingers anthropomorphic robot hand

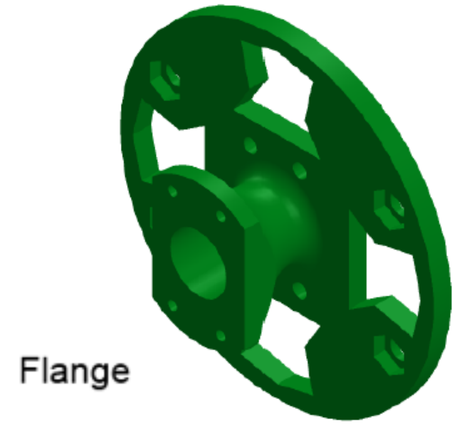




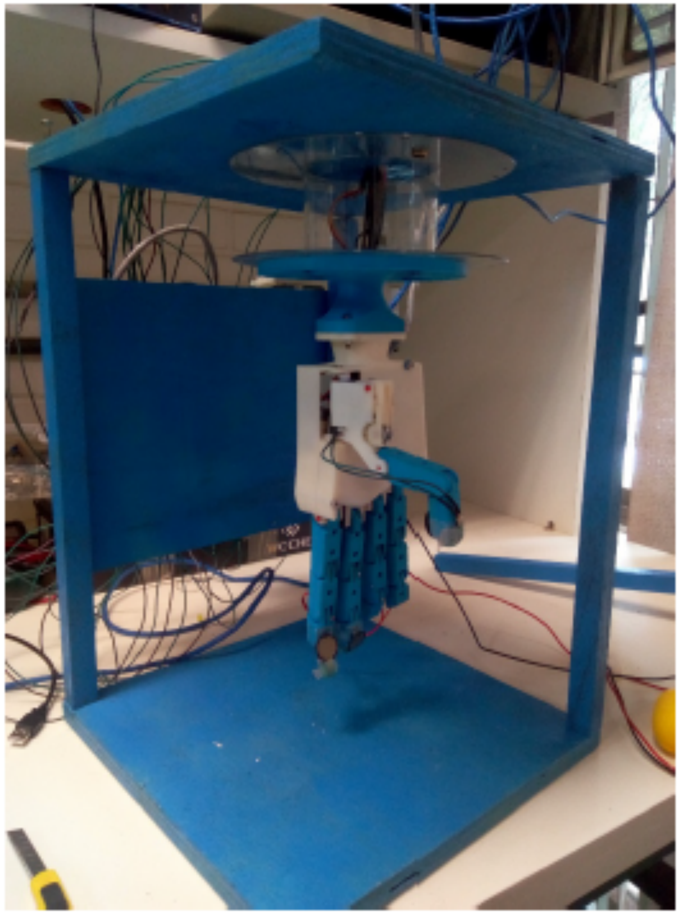
Detailing of palm and flange

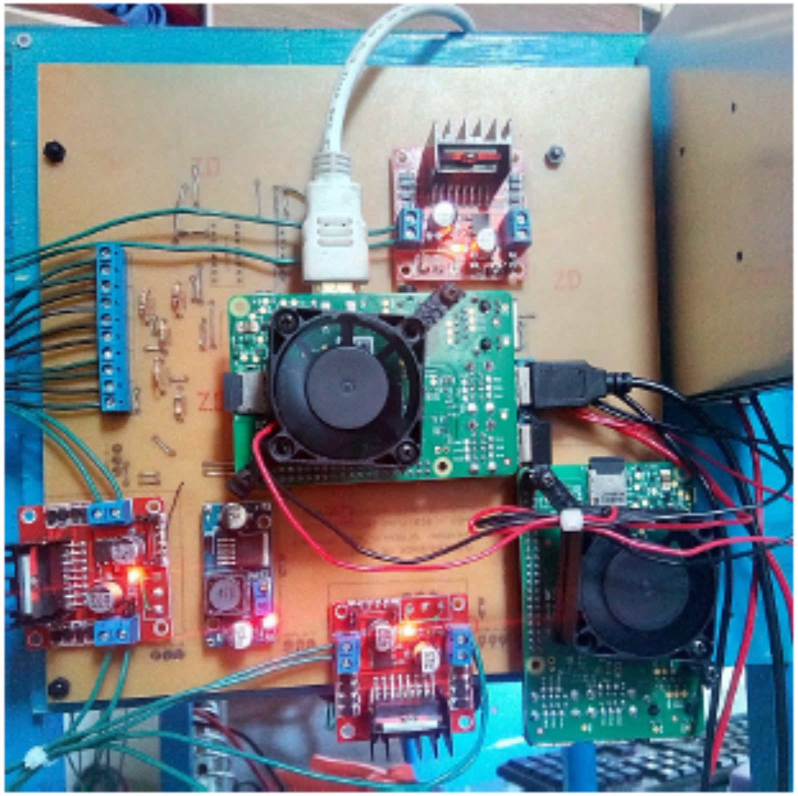




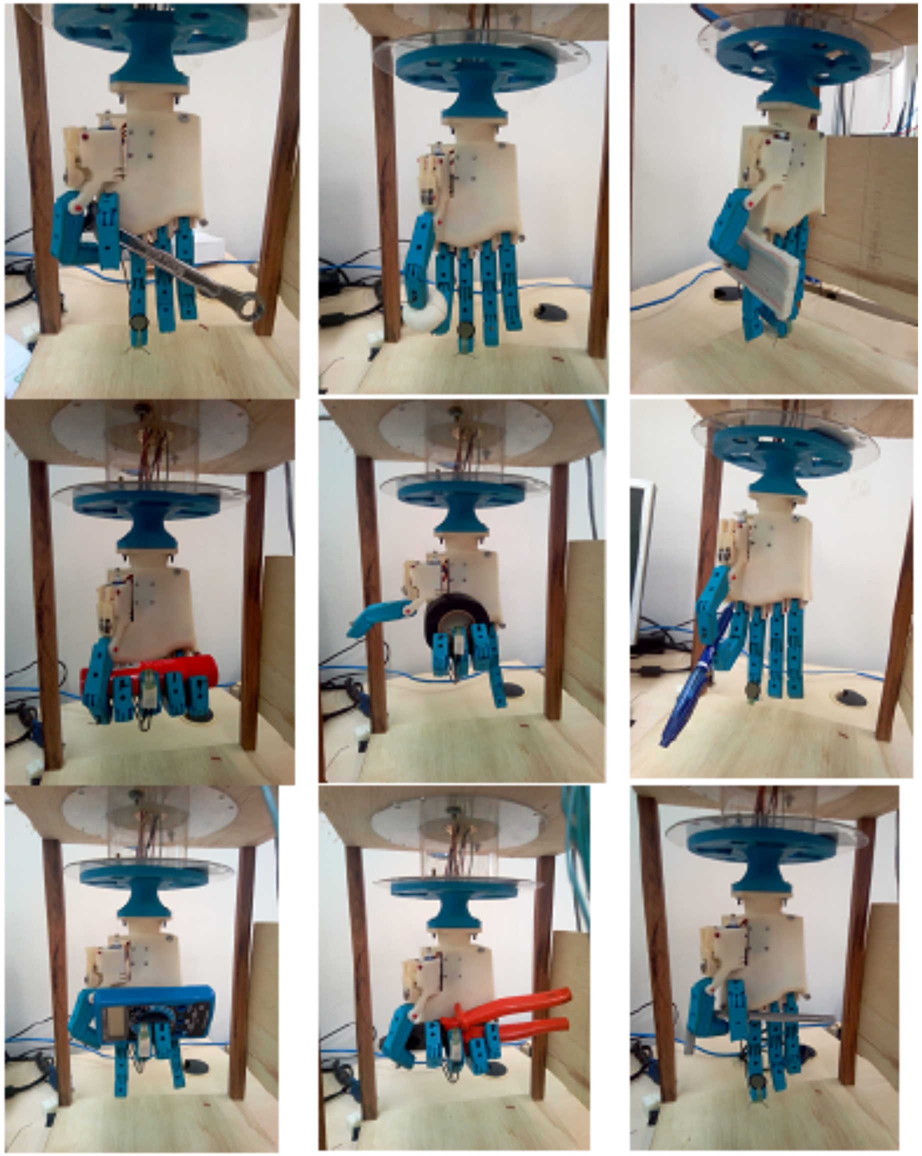


Prototype of the anthropomorphic robotic hand



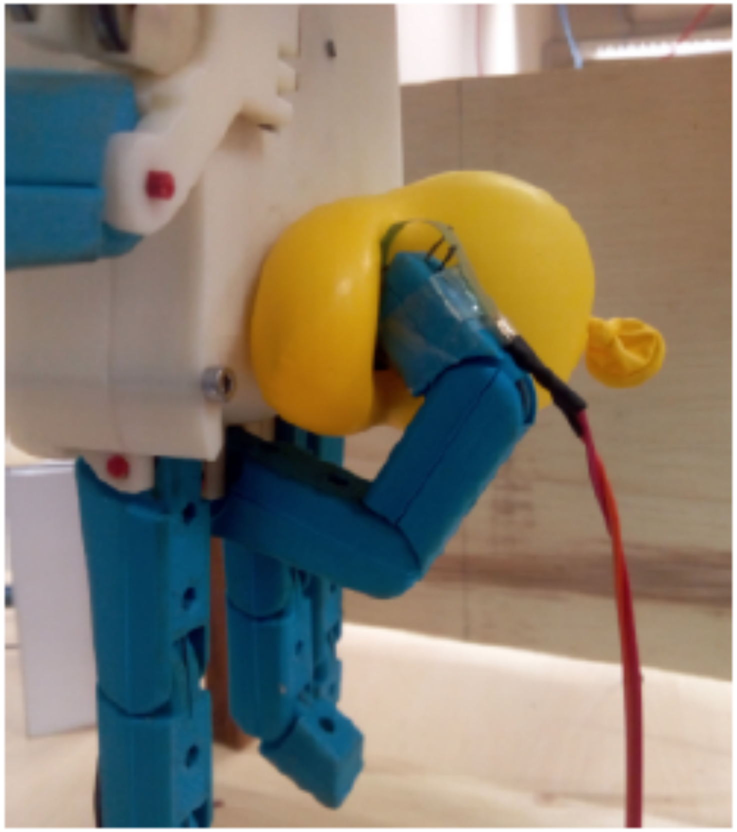


Manipulation of Objets



Hand with and without compliance control

(a) Hand with compliance control



(b) Hand without compliance control

Items reached summarized

Product Requirements	Target Specification	Reach the Goal?
Number of fingers in the hands	5	Yes
Force measuring sensor	Direct Measurement	Yes. Through the FSR sensor
Max capacity of manipulation	2 Kgf	No. Max force 0,8 Kgf*
Compliance control	Fuzzy Logic	Yes
Graphic interface	Python	No. Node-Red*
Fixation system	Flange	Yes
Control system accuracy	95%	Not estimated*
Total cost of production	US$ 500	US$ 528
Products found nationally	-	Yes
Degree of freedom	15	Yes
Possessing mounting modules	-	47
Forms of canonical force	4	Not estimated*
Canonical shapes of precision motion	4	Not estimated*
Power consumption	500 W	Yes
Programmable componetes open-source	Open-Source	Yes

* Obs: Items not satisfactorily achieved or not estimated

Items not satisfactorily achieved or not estimated

- **Max Capacity of manipulation**: According to the datasheet of the motor used, it has 1kg/cm.
- **Graphic interface:** generation of the graphical interface had to be performed through the Node-RED software to enable the decentralization of the client-control system to maintain system efficiency.
- **Control system accuracy:** according to the author's limitations, it was not possible to estimate the accuracy of the control system developed.
- **Forms of canonical force and canonical shapes of precision:** movements of the fingers occurred in a general way, since there is a need to make improvements in the gripper to allow classification of the grip.

Conclusion

- The adopted product development technique proved effective for the development of the anthropomorphic robotic hand.
- The behaviour of underactuated fingers can be substantially enhanced with tactile information and a classic fuzzy control approach.
- Only 4 items out of 15 of the target specifications required in the anthropomorphic robotic hand were not satisfactorily achieved or not estimated.
- The compliance control system developed the response time was about 300ms for the 5 fingers.
- In order to achieve a better interaction between object and finger, another mechanism for the fingers will be constructed. Strain gauge sensors will be used to read finger strength.

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Contact: alvares@AlvaresTech.com

PPMEC | Pós-Graduação em Sistemas Mecatrônicos
Faculdade de Tecnologia
Departamento de Engenharia Mecânica

Universidade de Brasília