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SIMULATION STUDY OF UNDERACTUATED HAND FOR GRASPING QUALITY

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Abstract. Existing pioneer designs of robotic hands such as DLR, MIT hand etc., have high dexterity but are bulky, costly and require a complicated control system. Research into under-actuated counterparts has produced interesting results but require further investigations into the grasping performance for regular objects. There is scope for multiple studies concerning existing under-actuated mechanical finger designs through simulation and experiments to ensure motion coherence, grasping stability and evaluating grasp quality. An under-actuated robotic gripper for a 3 finger, 6-DOF gripper is modelled to obtain a valid grasp hand configuration. Analysis of the under-actuated grasp system to obtain solution to linearized grasp system. Also, determination of values of several grasp quality metrics for the given configuration is undertaken.

Keywords: under-actuated finger, grasp model, grasp quality.

1. Introduction

Grasping is an important function for robots but for unstructured environments, diverse grasping seems essential to handle objects of various shapes and sizes. The human hand has been the most dexterous hand in sight and hence many researchers have conventionally imitated structure and grasping mode of human hand [1-4]. Belter and Dollar [5] have compared the general features of 5 commercial and 11 research hands such as type and the number of motors, degrees of freedom (DOFs), coupling methods with phalanges, range of motion of the joints, and the amount of forces applied in different grasp patterns. In addition to investigating the human grasp patterns and various driving systems, Controzzi et al. [6] have compared the specifications of several prosthetic hands in terms of actuators, sensors, kinematics, and the materials used in the prostheses. Melo et al. [7] have assessed the technical characteristics of 27 robotic hands regarding DOFs, actuator system, and sensing process. They have also introduced the grasp patterns and the control strategies in hand prostheses.

Greater focus has been built up on control and design of under-actuated systems, whose number of control inputs is less than DOFs. Under-actuation is an interesting route as it simplifies path planning and control of the robot gripper by changing some amount of active control needed for grasping to a passive mechanical system. Some models of under-actuation make use of mechanisms that are pulley or tendon driven. The advantages include lesser mass, less actuators and greater flexibility. On the other hand, demerits include limited load bearing and higher wear. Linkage based mechanical models leading to modification of existing fully actuated systems like LARM have also been studied in the past [8]. Many robotic hands were developed based on the studies conducted in these models [9], [10]. Some were developed with a desire for reduced cost setting 3D printable models into popularity [11]. Numerical analysis for under-actuated finger mechanisms developed and simulation methods have also been proposed for various designs. Research on the optimal design of under-actuated robot grippers continues to be driven by a desire to decrease the complexity and cost of grippers while maintaining the functionality of more complicated hands. In [12] the design methods and theoretical analysis of under-actuated finger mechanisms have been reviewed alongside presenting several prototypes of under-actuated fingers; i.e. less motors than the DOFs [13]. Different methods to drive the prosthetic fingers such as a combination of links, tendons [14], gears [15], cam [16], and combined driving systems have been employed in past research [17]. The majority work details the phalanges of fingers that are coupled by linkage or tendon. Many have contrasted these two types of coupling between phalanges [18]. Tendon-driven mechanisms have light and simple structure with a straightforward under-actuation. On the contrary, the linkage types are able to extend larger forces, less friction, with repeatable operation over long periods of time.

A method to simulate an under-actuated finger mechanism considering the mechanism's kinematic and static analysis for the sake of design implementation was set up by Wu [19]. A numerical case study was performed and simulated using specific code with MATLAB program. The results obtained confirmed that the proposed design of a new underactuated finger mechanism could give good grasping and be fit within the internal body of the phalange with a normal finger mechanical design.

Wu et. al. [8] also studied the performance and analysis characteristic of an underactuated finger mechanism using numerical simulation. Spring elements were considered of use as the passive elements that provide under-actuation to the mechanism. The results showed good capacity for grasping a multiple scales of object shapes and sizes by using the mechanism inside body of the finger. Based on the conducted study, a CAD model for the design was also proposed.

2. Modelling Under-Actuated Gripper

2.1. *Design Principle*

Assume a mechanism for a finger with a single degree of actuation and 2-DOF. A passive element is placed connecting the two digits and functions as actuating element for the second DOF. At rest, the two digits are kept in a neutral position with spring and mechanical stop. The actuator is then used to close the finger on the object. When contact occurs between object and first digit, the spring is extended by the actuator force, which pushes the mechanical stops apart, and the object comes into contact with the second digit.

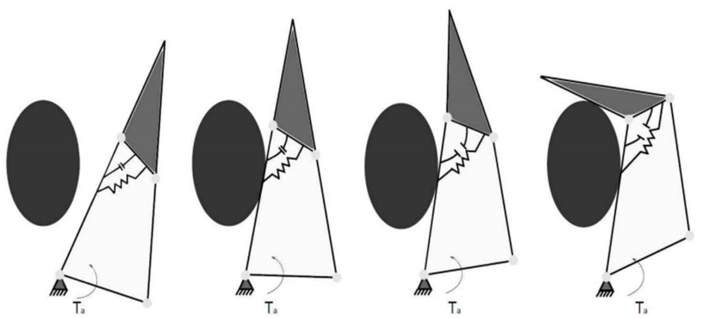

Figure 1. Closing sequence of 2DOF under-actuated finger [21]

The two digits each receive a portion of actuator force which allows finger to adapt to the object's shape and size. Initially due to lack of any external input, the finger travels like a rigid body until first digit contacts the object. Then the distal digit begins travel around a hinge end to perform a full wrap. This completes the closing sequence of the under-actuated finger. The principle can also be extended up to n-digit fingers but requiring accurate finger mechanism analysis to determine parameters for the passive elements present. Due to minimal grasping force and load carrying capacity of tendon actuated systems it is preferred to confine design to a linkage driven mechanism in the study which also proves advantageous due to low friction compared to tendon systems. The design chosen for study is adopted from the work done by Birglen and Gosselin [20].

2.2. *Kinematic and Static Modelling*

Consider {M} is a fixed inertial frame of reference. Also object coordinate system {A} is placed with origin relative to {M} by a vector d. The position of contact point i in {M} is represented by a vector ci. At contact point i, we denote a frame {C}i , with axes {ˆt_i , nˆ$_i$, oˆ$_i$}. The unit vectors tˆ$_i$ and oˆ$_i$ lie in contact tangent plane orthogonal to each other while the unit vector nˆ$_i$ is normal and toward the object. Say that joints are from 1 to 5 as in figure 2. Then consider that q = [q1 • • • q5]^T represent joint displacement vectors. Also assume τ = [τ1 • • • τ5]^T denotes torques at joints.

These torques can result from force of actuator, inertial forces or from object hand contact. Let f ϵ R3 be the force applied to the object at the point d and let mu ϵ R3 be the applied moment. Then resultant twist is $\omega = [f^T\ m^T]^T \epsilon\ R^6$

The main assumptions for Modelling include:

1. Passive element forces have negligible role and can be neglected in static analyses.
2. Inertial forces induced by motion of digits are minimal compared to grasping forces and can be neglected.
3. Friction between joints can be neglected.

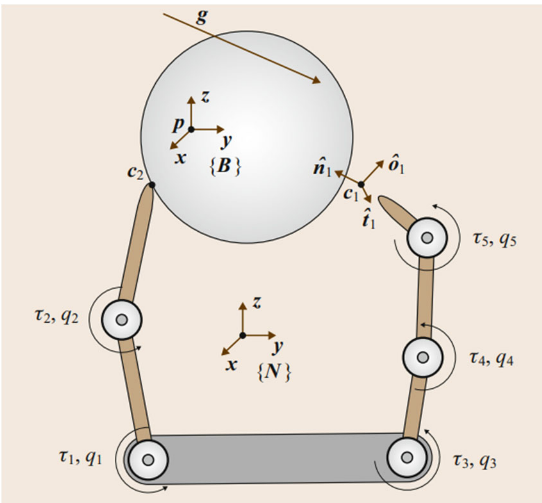

Figure 2. Main quantities for grasp analysis [22].

For grasp analysis, object position can be represented with frame {A} on object relative to stationery frame {M}. Let u ϵ $\Re^6$ denote the vector representing the position and orientation of {A} relative to {M}. Let $\nu = [v^T\ \omega^T]$ T ϵ $R^{n\nu}$, the twist of the object described in {M}. At each contact point i, the contact model chooses contact force λi ϵ $\Re^3$ (for hard finger model) [22] to represent constraints imposed by contact between object and the hand. Taking into consideration the reasonable assumptions, a quasi-static system is found useful to model the behaviour of the finger grasping the object.

The torque and force applying on the 'hand and the grasped object' system are the object twist w, the torques applied at joints, τ and contact forces λ at object hand interface at the contact points. The contact forces on the hand are balanced by the joint torques.

The static equilibrium of the hand and of the object is given by

$$\tau = J^T\lambda \tag{1}$$

$$w = -G\lambda \tag{2}$$

where G is the grasp matrix. The displacement of the contact points on the object δc^o to the object reference system displacement δu by the following congruence equation:

$$\delta c^o = G^T \delta u \tag{3}$$

The Jacobian matrix relates the displacement of the contact points on the hand δc^h to the joint displacement δq by the following congruence equation:

$$\delta c^h = J \delta q \tag{4}$$

The relation between the joint torques and the synergy torques is given by:

$$\sigma = S^T \tau \tag{5}$$

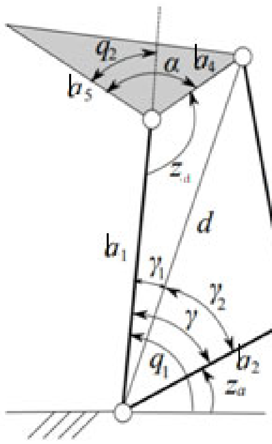

Figure 3. Under-actuated hand with Passive joints, Kinematics of one of the fingers [22].

2.3. *Under-Actuated Robotic Hand*

Consider the robotic hand with three fingers, composed of two digits each (with the same lengths) for a total of 6 DoFs. The fingers are actuated with a mechanism using small motors and springs. There are four revolute joints with each finger and we regard contact points on the links b_1 and b_5. The angles q_1 and q_2 are used for grasp analysis. Each finger is actuated by one motor [24] for the link b_2 and has two DoF's. The remaining phalanxes are passive actuated. A different variable, z_d portrays the arrangement of finger, the angle between links b_1 and b_4. Then, for each finger we have $z_i = [z_a,z_d]^T$, where the joint variable are q_1 and q_2. We observe that

$$q_2 = \alpha + z_d - \pi \quad (6)$$

where α is the angle between links b_5 and b_4, constant. Also,

$$q_1 = z_a + \gamma \quad (7)$$

$$\gamma = \gamma_1 + \gamma_2 \quad (8)$$

$$\gamma_1 = \frac{\arccos(b_1^2 + d^2 - b_4^4)}{2b_1 d} \quad (9)$$

$$\gamma_2 = \frac{\arccos(b_2^2 + d^2 - b_3^4)}{2b_2 d} \quad (10)$$

$$d = \sqrt{b_1^2 + b_4^2 - 2b_1 b_4 cos z_i} \quad (11)$$

The synergy matrix S is obtained as

$$S = \begin{bmatrix} S_i & 0 & 0 \\ 0 & S_i & 0 \\ 0 & 0 & S_i \end{bmatrix}$$

Where,

$$S_i = \begin{bmatrix} \frac{\partial q_1}{\partial z_a} & \frac{\partial q_1}{\partial z_d} \\ \frac{\partial q_2}{\partial z_d} & \frac{\partial q_2}{\partial z_d} \end{bmatrix} = \begin{bmatrix} 1 & \frac{\partial \gamma}{\partial z_d} \\ 0 & 1 \end{bmatrix}$$

2.4. *Numerical Simulation*

Considering the under-actuated 3 finger, 6 DOF hand model as defined in previous section modelling and analysis is carried out using SynGrasp toolbox in Matlab [23]. The grasp model incorporated a hard contact friction model and considers precision grip at fingertip contact as a means to grasping and associated analysis. Geometrical parameters and initial configuration were defined with values as shown in Table1.

Table 1. Geometric parameters and initial configuration.

Parameters	**Value**
b_1	38
b_3	35
b_2	20
b_4	15
α	$\frac{3}{4}\pi$
Z_a	$\frac{\pi}{6}$
Z_d	$\frac{2}{3}\pi$

3. Results and Discussion

The corresponding hand configuration was obtained by defining synergies, contact points and using function SGmovehand to move to the final configuration. The non–linear term in the synergy matrix was also obtained. The solution of the linearized grasp system was also calculated using the SynGrasp function SGQuasistaticMaps where the matrix P that represents the contact forces was determined. The values of matrix V representing object motion, Q for hand joint displacements, T for joint torques and Y for the actual synergy values was also obtained. Material for experimental validation can be 3D printed and elastic actuators producing joint and contact stiffness corresponding to simulation. The grasp quality for given configuration is determined using several metric values consisting of:

- SGdistSingularConfiguration -Quality measures related to the configuration of fingers and distance to singular configurations. This group of quality measures looks at configuration of the robotic fingers to estimate the grasp quality. It is valuable to have a high value for the hand Jacobian's lowest singular value SminJ. Considering SminJ as a quality measure, maximizing the quality helps choose a grasp configuration far away from a singular one. Then:

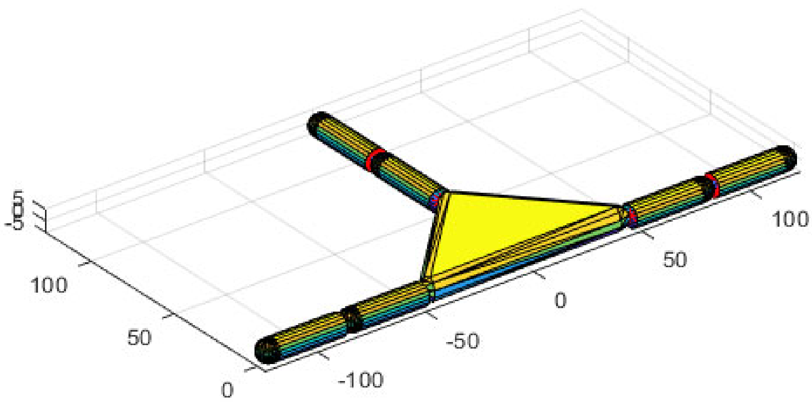

Figure 4. Initial Configuration 3 finger, 6DoF hand.

- SGgraspIsotropyIndex - Quality measures aligned with the points of contact. Properties of grasp matrix G made use of for measurement of quality. Here, contact forces present in twist desirably equivalent. It is taken as: Q=SminGSmaxG This value goes closer to 0 when the grasp is closer to a singular configuration and rises to 1 for nearly isotropic grasps.

- SGminSVG - Considers the lowest singular value of matrix G. This measure determines the lowest singular value of matrix G. In singular position grasps, minimum 1 of singular values falls to nil. Hence, the lowest singular value of the grasp matrix G, SminG, is used to determine the nearness to a positional singularity. Q = SminG. The lower SminG value is, the lower quality the grasp. Also at lower SminG, lower the transfer gain from contact points forces to the net twist on the object, considered as grasp improvement criterion.

These specific evaluations of geometric relations regarding contact points and configuration of fingers are shown as quantitative measures to represent grasp quality.

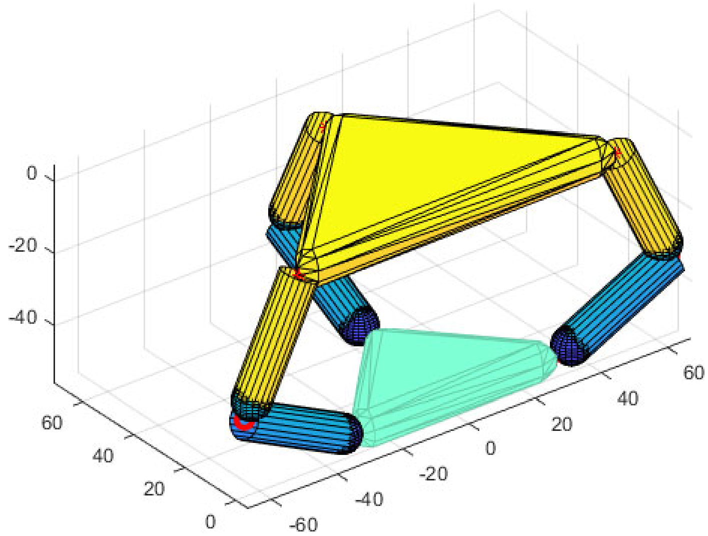

Figure 5. Final configuration 3finger, 6DoF hand grasping with 3 contact points.

The corresponding values of grasp quality for the numerical simulation were obtained as in Table 2.

Table 2. Pixels/cm Calculation

Quality Measure	DTSC	GII	MSVG
Value	$6.4523e^{-09}$	0.0339	1.7321

4. Conclusion

An under-actuated 3 finger robot gripper with 2DOF each was simulated using SynGrasp Toolbox in Matlab. Corresponding hand configuration was plotted along with non-linear component of synergy matrix and the linearized solution of grasp system was obtained using Syngrasp functions to obtain contact forces, joint torques and synergy actual values. The grasp configuration quality was measured using three different grasp quality metric systems- SGdist Singular Configuration, SGgraspIsotropyIndex and SGmin SVG and tabulated in Table 2. The result showed a weak quality of grasp that would give clarity to optimal grasp configuration in grasp manipulation studies. Future work includes stability and grasp compliance analysis for multiple starting configurations to obtain best grasp according to quality metrics and analysis for power grasp in under-actuated mechanisms.

References

1. Arockia Doss A.S., Mishra B., Mohammed S., Lingampally P.K., and Short M., Robotic Arm for Biomedical Applications. In: Hussain C.M., Di Sia P. (eds) Handbook of Smart Materials, Technologies, and Devices. Springer, Cham. https://doi.org/10.1007/978-3-030-58675-1_38-1 (2021)
2. Sonar K.R., Sai Sudeep Reddy S., Schilberg D., and Arockia Doss A.S., Design of Low-Cost Soft Angle Exoskeleton Using Soft Actuators. In: Hussain C.M., Di Sia P.

(eds) Handbook of Smart Materials, Technologies, and Devices. Springer, Cham. https://doi.org/10.1007/978-3-030-58675-1_37-1 (2021).

3. Arockia Doss, Arockia Selvakumar, and Hemkar Sharma. "Analysis of Fiber-reinforced Soft Bending Actuators on Various Parameters for Hand Rehabilitation." In Advances in Robotics-5th International Conference of The Robotics Society, pp. 1-6. (2021) https://doi.org/10.1145/3478586.3478587.
4. Gowrishankar, G., and A. Arockia Selvakumar. "Detection And Manipulation Of Pneumatic Walking Assistive Device Using Integrated System And Ann Classifier." Solid State Technology 63, no. 6 (2020): 10209-10221.
5. Belter A. M and Dollar, Performance characteristics of anthropomorphic prosthetic hands. IEEE Int Conf on Rehabilitation Rob, IEEE 2011, pp. 1-7 (2011)
6. M. Controzzi, C. Cipriani, M.C. Carrozza: Design of Artificial Hands: A Review. Springer, pp. 219-246 (2014)
7. E.N. Gama Melo, O.F. Aviles Sanchez and D. Amaya Hurtado, Anthropomorphic robotic hands: a review, Ing. Desarro. 32, 279–313 (2014).
8. S. Yao and L. Wu, Grasping simulation of an underactuated finger mechanism for LARM hand, Intl. J., Modelling and Simulation, vol30, (2015)
9. M. Baril, T. Laliberté, C. Gosselin and F. Routhier: On the design of a mechanically programmable underactuated anthropomorphic prosthetic gripper, J. Mech. Des. 135 (2013).
10. B. Peerdeman and M. Valori, UT hand I: a lock-based underactuated hand prosthesis, Mech. Mach. Theory 78 (2014).
11. Li-Cheng Wu and Xia-Li Li, A 3D-printed Robot Hand with Three Linkage-driven Underactuated Fingers, Int. J. Automation and Computing, 2018
12. Ciccarelli M and Z. M, Robotica, Design and simulation of an underactuated finger mechanism for LARM Hand, vol35, Cambridge Press, (2017).
13. Birglen, L., Laliberte, T., and Gosselin, C. M, Underactuated Robotic Hands, Springer-Verlag, Berlin, Heidelberg, Vol. 40 (2008).
14. E.N. Gama Melo, O.F. Aviles Sanchez and D. Amaya Hurtado, Anthropomorphic robotic hands: a review, Ing. Desarro. 32, 279–313 (2014)
15. Y. Hirano, K. Akiyama, R. Ozawa, Design of low-cost and easy-assemblable robotic hands with stiff and elastic gear trains, in: 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE , pp. 864–870 (2016).
16. S. Tan, W. Zhang, Q. Chen and D. Du, Design and analysis of underactuated humanoid robotic hand based on slip block-cam mechanism, in: 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO), IEEE pp. 2356–2361 (2009).
17. Amudhan, S., M. Arul Kumar, and A. Arockia Selvakumar, Design and Analysis of Electronic Controller Based Robot Arm, Applied Mechanics and Materials. Vol. 813. Trans Tech Publications Ltd (2015).
18. D. Yoon, G. Lee, S. Lee and Y. Choi, Underactuated finger mechanism for natural motion and self-adaptive grasping towards bionic partial hand, in: 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), IEEE, pp. 548–553(2016).
19. L. Wu, A Numerical Simulation for Design and Operation of an Underactuated Finger Mechanism for LARM Hand, Int. J. Mech. Based Des. Struct. Mach (2009).
20. L. Birglen and C. M. Gosselin: Geometric Design of 3-Phalanx Underactuated Finger, J Mech Design, ASME (2006).
21. L. Birglen, C. M. Gosselin: Kinetostatic Analysis of Underactuated Fingers, IEEE Tr., Robotics and Automation (2014)
22. D. Prattichizzo and J. Trinkle, Chapter 28: Grasping,Handbook on Robotics (B. Siciliano and O. Kathib, eds.) , pp. 671–700, Springer (2008).

23. Malvezzi, M., Gioioso, G., Salvietti, G. and Prattichizzo, D. SynGrasp, A MATLAB Toolbox for Underactuated and Compliant Hands. Robot, Autom. Mag. IEEE 2015, 22, 52–68 (2015).
24. M Venkatesh V, G Naleshwarkar and Arockia Selvakumar A., Gesture Control Robot With Adaptive Gripper, International Journal of Pure and Applied Mathematics 114.11 (2017): 301-311 (2017).