Design and Synthesis of a Four Fingered Articulated Dexterous Robot Hand

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Abstract— **The human hand with more than twenty seven Degrees of Freedom (DoFs) has a unique musco-skeletal structure with neuro-sensory attributes under control of CNS, is a quintessence to construct a robotic hand. The fingers are connected to the palm with metacarpo-phalangeal (MCP) joints. These joints have two DoFs i.e. flexion-extension and abduction-adduction whereas the remaining two joints of the digits have only one DoF. Literature survey divulges that, while constructing a robotic hand, mostly the abduction-adduction at MCP joint is discarded for simplicity. This paper is aimed at development of a mechanism that encompasses both flexion-extension and abduction-adduction for all the three fingers located on the palm opposite to the thumb, whereas the thumb has been separately designed to impart both the radial and palmer movements with respect to the palm as well as flexion and extension, thereby imparting greater compliance to the system, to cope up with wide variety of tasks.**

Keywords—degrees of freedom; robot hand; flexion/extension; abduction/adduction;

I. INTRODUCTION

The current generation industrial grippers do not entail all kinds of grasping modes, and suited for specific industrial applications. In order to design a general purpose gripping device, an anthropomorphic approach is essential. Human hand being the existence proof of all successful gripping devices motivates the researchers to replicate the attributes; the human hand is bestowed with. Designing system like us seems to be a daunting task because of the constituent muscoskeletal system under supervision of thousands of sensory neuro-motors. Bicchi [1] emphasized that, during design of hands for dexterous manipulation and robust grasping, rather than mimicking it; attention may be given pertinent to its functional attributes. Keeping in view the same, present investigation aims at designing an anthropomorphic robot hand which partially resembles a human hand with four fingers poised with the feasible flexion-extension as well abduction-adduction motions with a suitably designed palm to accomplish tasks. Previous designs of fingers in anthropomorphic robotic hands [2, 3, 4, 5, 6] have all employed either tendons which leads to permanent set, thus decreasing the system repeatability or pneumatic systems which require a robust actuation and control system. The chronological development of the robot hands has been shown in Table-1.

Table-1: Chronological Development of Robotic Hands.

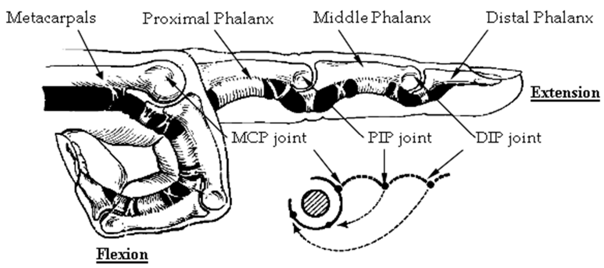
Author	Hand &Year	DOFs	Actuation type	Number of fingers	Provision for Abduction-Adduction	Nature	Remarks
Bekey et. al. [7]	Belgrade/ USC Hand [1969]	4	Linkage	5	No	Under actuated	Anthropomorphic Hand
Mason and Salisbury [8]	Stanford/JPL Hand [1981]	4	Tendon operated	3	Yes ±45°	Under actuated	Two fingers with thumb in oppose
Jacobson et. al. [9]	UTAH/ MIT Dexterous Hand [1982]	16	Tendon driven	4	Yes	Dependent and under actuated	Complex control architecture, friction between pulley and tendon.
Lovchik and Diftler [10]	Robonaut Hand [1999]	11	Tendon with lead screws	5	Yes ±45°	Dependent motion present and partially under actuated	Angles of the phalanx are not compatible with the human hand.
Casalino, G. [11]	DIST Hand [2000]	16	Tendon operated	5	Yes	Under actuated	tendon actuation mechanism degrades the repeatability
Hirzinger, G. [12]	DLR II Hand [2001]	13	tendon	4	Yes	Dependent motions	High cost involvement
Fukaya et. al. [13]	TUAT/Karlsruhe Hand [2002]	1	linkage	5	Yes	Under actuated	Dexterity is very less
Cheng et. al. [14]	LARM Hand [2009]	3	linkage	3	No	Under actuated	Non anthropomorphic hand

Based on the literature review, the present work is aimed at development of a direct linked dexterous four fingered eleven degrees of freedom robotic hand where each degree of freedom is dictated by a single actuator. The employment of more numbers of actuators increases the dexterity as well as repeatability of the system at the cost of complexities evolved from programming and control strategies. Tradition tendon actuated system has not been adopted herein due to lack of repeatability. The master slave control strategy has been adopted in the present investigation.

II. DESIGN AND SYNTHESIS

The human hand poses different motion characteristics like adduction/abduction and flexion/extension has been shown in Figure1 (a) and (b). The typical ranges of phalanx motions have also been shown in Table 2. The requirement for the design was to develop a four fingered robot hand with same aspect ratio that of a human hand consists of a thumb and three fingers namely; index, middle and ring. For simplicity the provision for little finger was discarded because in precision and power grasp the contribution of the little finger is very less with respect to the other four fingers.

(a)



(b)

Figure 1: The Fingers Motions. [15][16]

Table-2 Typical Range of Phalanx Motions [16]

Joints	Articulation type	Angle (in degree) average value
Thumb basal joint	Palmer Adduction/Abduction	45°
	Radial Adduction/Abduction	60°
Thumb DIP joints	Extension/Flexion	80°
Thumb MCP joints	Extension/Flexion	80°
Finger DIP joints	Extension/Flexion	80° - 90°
Finger PIP joints	Extension/Flexion	90°-100°
Finger MCP joints	Extension/Flexion	-15° to 85°

III. SYNTHESIS FOR RANGE OF MOTIOIN

Literature survey reveals, in most of the robotic hands, power is differentially transmitted from the proximal end to the distal end of the fingers. Objective of this project was to locate all the BLDC motors to the back of the palm and subsequently to draw the motion upto the distal end. During the synthesis for flexion/extension motions at MCP (Metacarpo-phalangeal joint), PIP (Proximal Inter-phalangeal Joint) and DIP (Distal Inter-phalangeal Joint) it has been observed that the motions at PIP and DIP occurs simultaneously and yields single degree of freedom (DoF). Eventually the synthesis for a single finger demands for coordinated flexion/extension of DIP and PIP joints and both flexion/extension and abduction and adduction at MCP joint and give rise to 3 DoFs. In human finger the flexion of the distal joint occurs simultaneously with proximal joint's flexion, thus this movement does not belong to active category rather; although in passive mode DIP joint can be independently actuated. Since the purview of the present work was aimed at active mode grasping, reveals interdependence of the two joints. The same has been adopted and inculcated herein as shown in Figure-3.

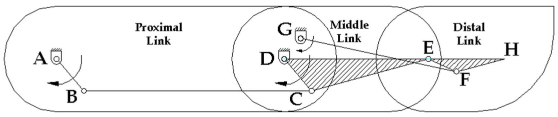


Figure 2: Kinematic Linkage Mechanism for Flexion and Extension at PIP and DIP Joints.

In Figure 2, it is evident that the rotation of the crank AB flexes the finger towards the volar side of the palm. The mechanism for actuation of the finger consists of two four bar linkages, ABCD and DEFG. As the crank AB rotates, it pulls the rocker CD, which is similar in length of AB about the proximal inter-phalangeal joint D. Again CDE forms a bell-crank, the input motion gets transmitted to turn the distal link EFH about the distal inter-phalangeal joint E. The intermediate quasi-static frames have been shown in Figure 3. The dimensional synthesis was done by utilizing the Freudenstein Equation in order to conform to the range of motion as per Table-1 [i.e. when the PIP flexes by an angle of 90° the DIP also flexes with the same angle, (156°-65°) =91°].

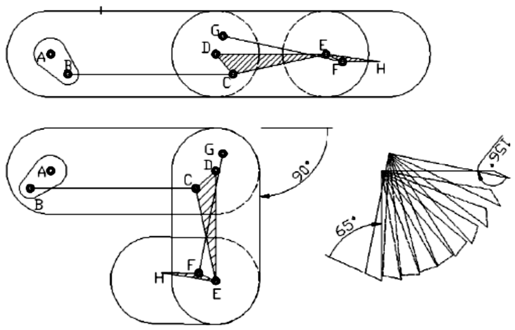


Figure 3: Quasi Static Frames during Finger Motion

Design for each finger utilized three motors has been as shown in Figure 5. Motor M1 is directly coupled to the centre cross which supports two sets of metre-gears (Pair-1 and Pair-2) freely on it and conduces the abduction/adduction at MCP. The second motor, M2 enable the flexion/extension at MCP joint by rotating the gears P1G1 with the help of timer belt and in turn rotates P1G2 which is connected to proximal link. The third motor, M3 ensure the combined flexion and extension of the PIP and DIP joints. Figure 5 illustrates the hardware subassembly for the middle finger. It is intended to apply flexion at MCP joint it is quite obvious that actuator which actuates the flexion at MCP will certainly influence the combined motion at PIP and DIP. Figure 4 depicts the movement of the crank by an angle of θ_1 (∠BAB') to flex the PIP and DIP simultaneously towards the palm. Again when the MCP is given an angular displacement of a_2 to flex the entire finger, it eventually reduces the angle of turn of the crank by the same and the effective angle of flexion of the crank becomes ∠B"AB (∠BAB' - ∠B'AB''= a_2-a_1) and extends the portion of the finger after PIP joint. This shows surely the dependence of motion by motor M2 and motor M1. The same has been mitigated through the additional motion of same amount (a_2) provided to the actuator (M1) that actuates middle and distal links.

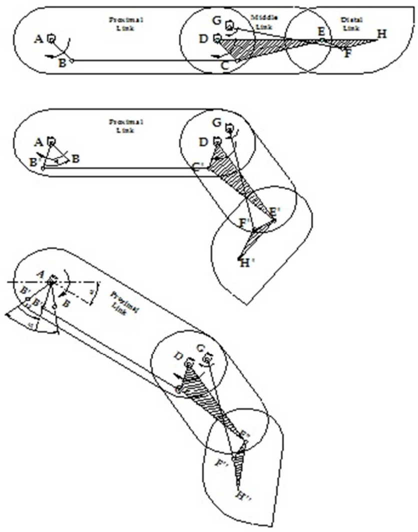


Figure 4: The dependence of MCP joint motion with PIP and DIP joints.

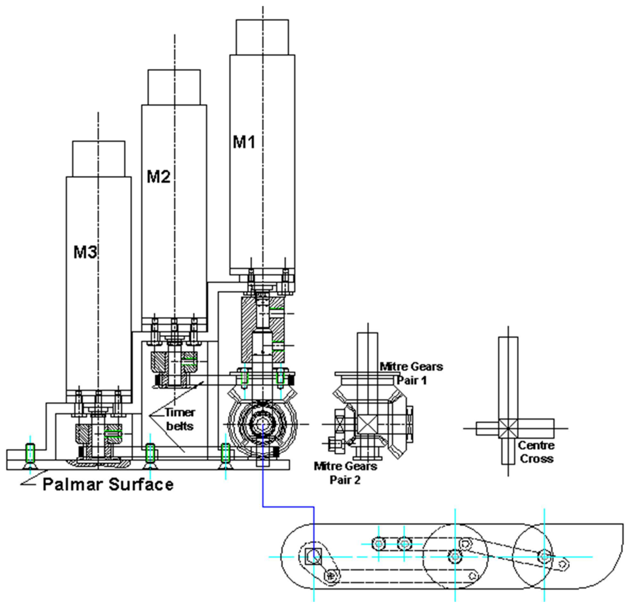


Figure 5: Quasi Static Frames during Finger Motion

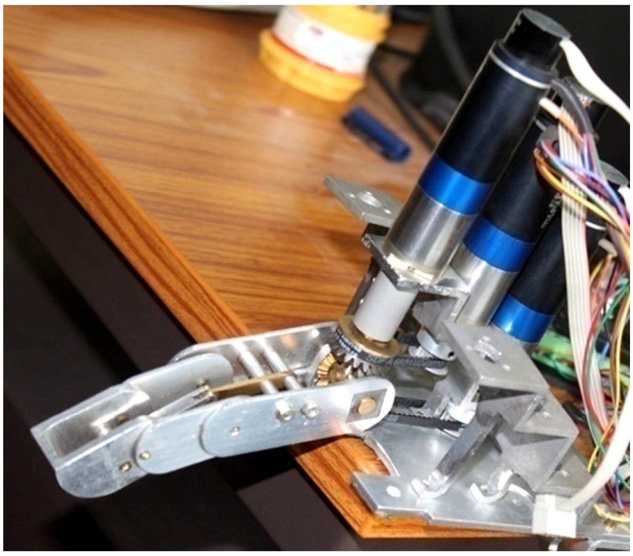


Figure 6: Quasi Static Frames during Finger Motion

Therefore it can be inferred one can independently actuate the motor M1 for simultaneous flexion of proximal and distal joint, but in order to ensure the motion at MCP joint through M2, the same amount of rotation has to be ensured for M1 to keep the flexion at DIP and PIP unchanged. This way of negation of interdependence seems to be a witty approach, giving rise to another degree of freedom. In a very similar manner motor M3 which is the deponent for abduction and adduction motion demands for motion requirement for both M1 and M2. As a coda it can be inferred in the following manner:

a) Motor M1 can independently actuate to impart combined flexion extension at DIP and PIP joints.

b) Motor M2 can be moved independently to ensure flexion extension at MCP if and only if the effect on motor M1 is taken care of by providing a signal the same amount of rotation.

c) Motor M3 can be moved to impart only abduction and adduction if and only if effects on M2 and M1 are mitigated.

Since the thumb has got two DoFs (one palmer and one radial), to incorporate the same two motors have been utilized. Motor M4 creates the radial motion to the base of the thumb Motor, M5 the combined motion for the phalanx of the thumb with the aid of one worm wheel pairs as shown in Figure 6.

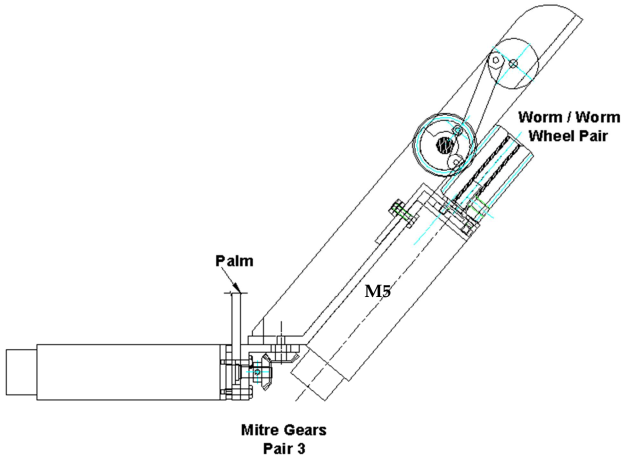


Figure 7: The Articulation of the Thumb

IV. KINEMATIC ANALYSIS AND CONTROL STRATEGY

Quasi-static motion as well as force analysis has been accomplished analytically. Figure 7 shows that the fingertip velocity initially increases and then decreases as the fingertip approaches the object (fine manipulation) whereas the grasping force imparted by the finger gradually increases to ensure a stable grasp, as evident through Figure 8.

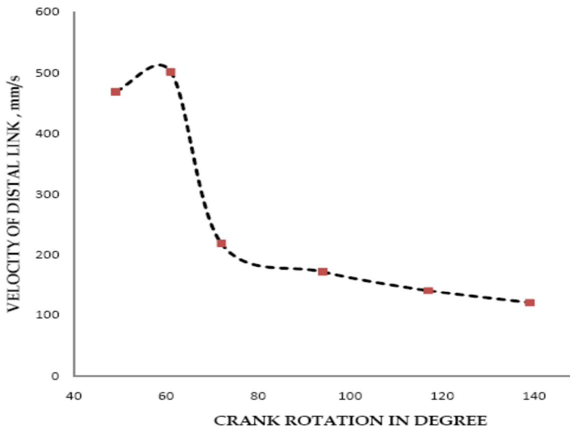


Figure 8: Motion characteristics of the fingertip

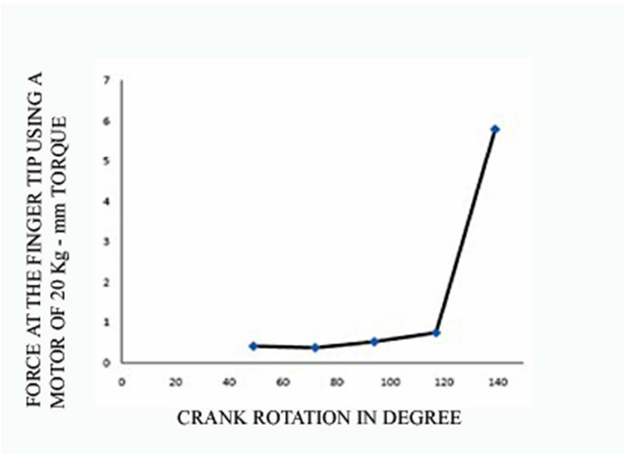


Figure 9: Force characteristics of the fingertip

The finger tip trajectory and the workspace of the designed finger were simulated without abduction and adduction and are shown in Figure 10 and Figure 11 respectively.

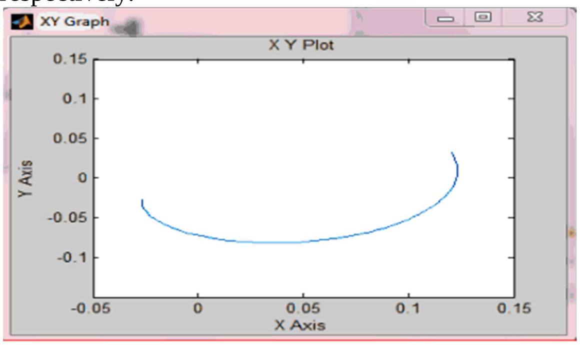


Figure 10: Fingertip trajectory of a single finger

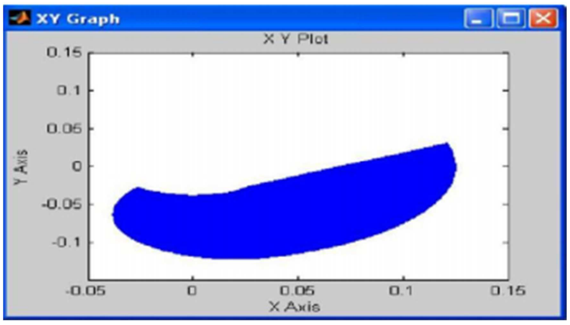


Figure 11: Workspace computation of a single finger

Control Strategy

The present control strategy targets in controlling the robot hand in master slave configuration. Human motions are captured using sensor integrated gloves and required control actions are taken to achieve the same. In the present framework direct angle mapping is being used to map the grasp from the human hand to the robot hand. The joint angle to be achieved is then fed to the individual controllers of each of the joints. The controllers are PIV based controllers that control individual joints as per the requirement from the mapping algorithm. Figure 12 summarizes the basic control loop for the open loop control of the robot hand.

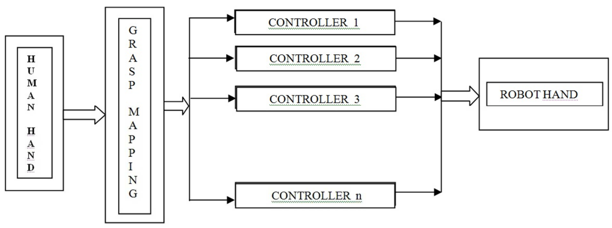


Figure 12: Open loop control strategy

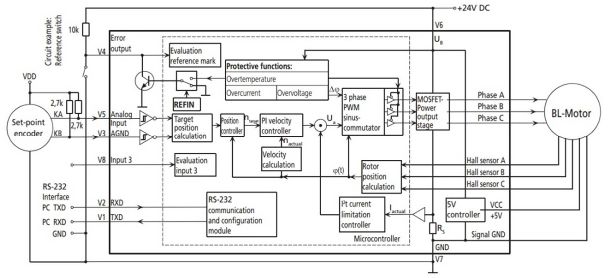


Figure 12: Circuit diagram of the controller. [17]

All the controllers have a unique identification number and are connected in daisy chain network. This means the mapping algorithm transmits the mapping result to all of the 11 controllers, but is accepted by the controller which has the required identification number. The control architecture of the controllers (Faulhaber MCBL 3003) is shown in Figure12. The complete hardware setup is shown in Figure 13.

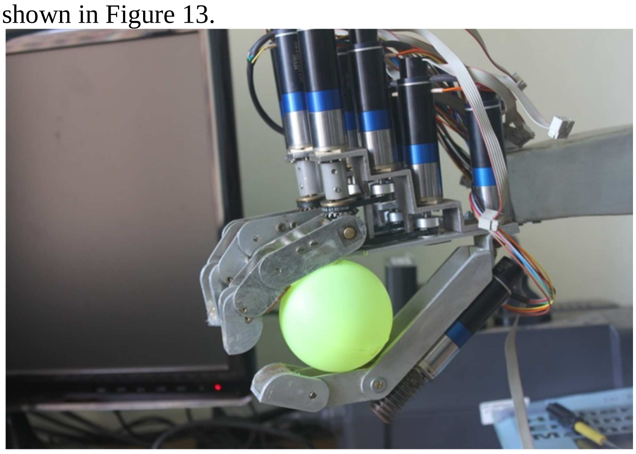


Figure 13: Dexterous hand

V. Conclusion

From the study of design of the multi-degrees of freedom finger poised with newly developed metacarpophalangeal joint, the following conclusions may be drawn:

i. The attributes of a human finger have been mapped to a robotic finger with a three DoF MCP joint in order to impart flexion-extension as well as abduction-adduction.

ii. The important issues with regard to the design of multi-DoF robotic finger have been addressed.

iii. The problems associated with tendon-operated robotic finger have been eliminated to an extent to mitigate the losses due to friction at the joints.

iv. The linkage mechanism of the finger confirms the range of movement as present in human finger.

v. During the trajectory planning, it has been observed that the finger is endowed with the modus-operandi of the human finger due to the presence of trade-off between the fingertip velocity and force exertion pertinent to the fine manipulation attribute.

vi. The fingers are able to abduct-adduct substantially.

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