Chapter 2  LITERATURE REVIEW

2.1 Introduction

The objectives of the research work are abstracted from the practical observations and from the need of gripper for various tasks in the previous chapter. Accordingly the required literature survey has been carried out in five specific areas. These selected areas related to MRG operations are as given below

I. Multifingered Robot Hand (MRH):- Types and their grasping mechanisms
II. Sensors for robot gripper :- Types of Materials and applications for various task
III. Vision System for grasping action :- Types of systems and their strategic usages
IV. Modeling & Simulations of robot gripper :- Types of gripper system models & its simulation for analysis
V. Biomimetic Design Approach :- Types of innovative mechanisms and their role in grasping action towards a search of universal grasper.
VI. Gripper Forces Determination and Kinetostatic analysis :- Types of analysis for force determination at grasping action.
VII. Controlling and System Programming: - Types of algorithms and use of newer tools in the area of control at hardware & software level.

The above mentioned separated topics give clear idea about the outline of the total research completed in these fields. Those are separated to get clear understanding in each respective area. Though titles / topics discussed in this way helps for better understanding the demarcation line for each topic from others is not distinctively separate. Hence information found in one topic may sometime covers more than single topic as mentioned above.

Multifingered Robot Hand (MRH) :-

Multifingered robot hands (MRH) have been developed as an attempt to mimic human hand functionality. Many such hands have been developed at the Universities, laboratories and few numbers by industries. Technically Multifingered Robot Hands (MRH) and Multifingered Robot Gripper (MRG) are two different terms. But most of the types of these two different classes are considered as Multifingered Robot Hands (MRH).
Chapter 2

Literature Review

Literature study for MRG / MRH explores the benchmark type of designs.

2.2 Multifingered Robot Gripper (MRG) / Multifingered Robot Hand (MRH)

Various types of hands are discussed and published by scientist, researchers and academicians. This study can focus more on the robot hand only. Prosthetic hands do posesses interesting designs and controls but those are not discussed / considered in detail. The evidences for the technical study and applications were found surprisingly from 15th century onwards, which include the most prominent ones as listed below.

1. Mechanical Hand designed by Dix livres de chirurgie, Paris [Fig 1] - 1564. [1]
2. Musician Hand, Jacquet – Droz, Switzerland [Fig 2] – 18th Century. [2],[3]
5. UTAH / MIT Hand, Utah University, Utah [Fig 5] – 1983. [7][8] &[9]
9. UB Hand II, Bologna University, Italy [Fig 9]– 1992. [4] [13]
10. Grasper Hand, North Eastern University, Boston , USA [Fig 10] 1996. [14]
11. DLR I Hand, DLR German Aerospace Center, Germany [Fig 11] – 1997. [4][15]
12. LMS Hand, Université de Poitiers, France [Fig 12] – 1998. [16][17]
13. DIST Hand, Università di Genova, Italy [Fig 13] – 1998. [4] [18]
14. Robonaut Hand, NASA Johnson Space Center, Houston, USA [Fig 14]–1999. [4] [19 ]
15. Tokyo Hand, University of Tokyo, Japan [ Fig 15 ] – 1999. [4][20 ]
16. Karlsruhe Dexterous Hand II, Univ. of Karlsruhe, Germany [Fig 16]–1999[4 ] [21][22]
17. Tuat / Karlsruhe Hand, Tokyo & Karlsruhe Universities, [Fig 17 ]-2000. [4][22][23]
18. Ultra light Hand, Research center of Karlsruhe, Germany [Fig 18 ] – 2000. [4][22][24]
19. TBM Hand, Toronto/ Bloorview Macmillan Hand, Toronto, Canada [Fig 19]–2001[25]
20. DLR II Hand, DLR German Aerospace Center, Germany [Fig 20 ] – 2001. [26]
21. Gifu Hand, Gifu University, Japan [Fig 21] – 2001. [4][27]
23. SSL Hand, Space Systems Lab. Univ. of Maryland, Boston, USA [Fig 23]– 2002. [29]
25. NAIST Hand, Nara Institute of Sci. & Tech.(NAIST), Nara, Japan [Fig 25] – 2005. [31]
26. SDM Hand, Harvard University, USA [Fig 26] – 2006 [32][33]
27. RL 1 hand Robotics Lab Universidad Carlos III de Madrid, Espana [Fig 27] – 2006 [34]
28. Ca. U. M. Hand, Cassino Underactuated Multifinger Hand, Univ. of Cassino, Italy [Fig 27] – 2007. [35]
29. LARM Hand, Lab. Of Robotics & Mechatronics, Univ. of Cassino, Italy [Fig 28] – 2008. [36]
30. Southampton Hand, University of Southampton, UK, [Fig 29] – 2000. [37][100]

Though hand designs are meant for robotics related applications few designs made for application in the prosthesis, are equally sophisticated. They possesses capability for their use in industrial robotic applications (e.g. Southampton hand. Multifingered Prosthetic hands like Otto Bock hand, VASI 7-11 hand, RTR hand, and Montreal hand are prosthetic grippers [4][38][39]) Earlier Hi-T Hand, Hitachi tactile controlled Hand, Hitachi Co., Japan in 1978 [98] is developed with simple two fingered gripper. Hence it is not considered for MRH related discussions as well.

Recently many scientist and researchers are concentrating on the fast action grippers. They are named as 100 G, 200 G...etc depending on the speed of grasping, e.g. High-speed Multifingered Hand developed at University of Tokyo, Japan [30].

Maximum designs employ a thumb which is rotating about desired axis as per the applications. The experimental hands include are not suitable for prosthesis and are meant for both delicate plus light weight and heavy duty applications.

Comparative study of these existing hands gives a clear understanding for types of grasping modality, level of dexterity and mechanisms involved. Though this type of comparison is already made it is mandatory to do it again for this work since the recent updates and more information through comparison can give a consolidated guidelines.
<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Name of MRH</th>
<th>No. of Finger Thumbs (Yes/No)</th>
<th>No. of Joints</th>
<th>DOF</th>
<th>Actuation Type</th>
<th>Transmission Type</th>
<th>Biomimetic approach (Y/N)</th>
<th>Sensor Type</th>
<th>University/ Organisation and a Person</th>
<th>Place of research, country</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mechanical Hand Design [1]</td>
<td>5 (Y)</td>
<td>17</td>
<td>---</td>
<td>Manual</td>
<td>Linkages</td>
<td>Yes</td>
<td>N.A.</td>
<td>Published by Dix livres de chirurgie</td>
<td>Paris</td>
<td>1564</td>
</tr>
<tr>
<td>6</td>
<td>Belegrade /USC hand [10][97]</td>
<td>5 (Y)</td>
<td>18</td>
<td>4</td>
<td>DC Motors</td>
<td>Linkages</td>
<td>Yes</td>
<td>Tactile</td>
<td>Barret Technology Incorporation</td>
<td>Townsend, USA</td>
<td>1988</td>
</tr>
<tr>
<td>7</td>
<td>Barret Hand [11]</td>
<td>4 (N)</td>
<td>8</td>
<td>4</td>
<td>Electric Revolute Motors (Brushless)</td>
<td>Spur and Worm Gear</td>
<td>No</td>
<td>Strain Gauges</td>
<td>Barret Technology Incorporation</td>
<td>Townsend, USA</td>
<td>1988</td>
</tr>
<tr>
<td>Chapter 2</td>
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<td>Literature Review</td>
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</tr>
<tr>
<td>10 Grasper Hand [14]</td>
<td>3 (Y)</td>
<td>11</td>
<td>11</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>North Eastern University, Boston, Massachusetts</td>
<td>1996</td>
<td></td>
</tr>
<tr>
<td>11 DLR Hand I [4][15]</td>
<td>4 (Y)</td>
<td>16</td>
<td>13</td>
<td>Electric Revolute Motors</td>
<td>Tendons and Pulleys</td>
<td>yes</td>
<td>x-y force sensor on fingertips</td>
<td>Tactile sensor in each finger link</td>
<td>Butterfuss 1999</td>
<td>DLR-German Aerospace Center</td>
<td>1997</td>
</tr>
<tr>
<td>12 LMS Hand [16][17]</td>
<td>4 (Y)</td>
<td>17</td>
<td>16</td>
<td>Electric Revolute Motors</td>
<td>Tendons and Pulleys / sheaths</td>
<td>yes</td>
<td>---</td>
<td>---</td>
<td>Gazeau 2001</td>
<td>University de Poitiers</td>
<td>1998</td>
</tr>
<tr>
<td>14 Robonaut Hand [4][19]</td>
<td>5 (Y)</td>
<td>22</td>
<td>14</td>
<td>Electric Revolute Motors (Brushless)</td>
<td>Flex-shaft + lead screw</td>
<td>yes</td>
<td>Force sensing resistors</td>
<td>Lovchik 1999</td>
<td>NASA Johnson Space Center</td>
<td>1999</td>
<td></td>
</tr>
<tr>
<td>16 Karlsruhe Dexterous hand II [21][22]</td>
<td>5 (Y)</td>
<td>24</td>
<td>1</td>
<td>Electric Revolute Motors</td>
<td>Link mechanisms</td>
<td>yes</td>
<td>Gripper state sensor for position and force sensor</td>
<td>Th. Fischer and J. Seyfried. 1997</td>
<td>University of Karlsruhe, Germany</td>
<td>1999</td>
<td></td>
</tr>
<tr>
<td>18 Ultra Light Hand [4][22][24]</td>
<td>5 (Y)</td>
<td>18</td>
<td>13</td>
<td>Pneumatic</td>
<td>Directly driven</td>
<td>yes</td>
<td>Pressure sensors</td>
<td>Kawasaki 2001</td>
<td>Research Center of Karlsruhe</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>TBM Hand [25]</td>
<td>5 (Y)</td>
<td>14</td>
<td>14</td>
<td>Electric Motors</td>
<td>Linkages, revolute &amp; knuckle joints, spring for fingers Pulleys and cables for Thumb</td>
<td>yes</td>
<td>Contact sensors</td>
<td>Toronto / Bloorview Macmillan Hand, Toronto, Canada</td>
<td>University of Toronto, Toronto, Canada</td>
<td>2001</td>
</tr>
<tr>
<td>23</td>
<td>SSL Hand [29]</td>
<td>4</td>
<td>12</td>
<td>12</td>
<td>Electric motors</td>
<td>Linkages and tendons</td>
<td>Hand- no, Arm- yes</td>
<td>Force and Torque Sensors</td>
<td>David L. Akin Craig R. Carignan Anthony W. Foster</td>
<td>Space System lab, University of Maryland, MD</td>
<td>2002</td>
</tr>
<tr>
<td>24</td>
<td>High Speed multifingered hand [30]</td>
<td>3 (yes – 2) one Index and two thumb</td>
<td>6</td>
<td>9</td>
<td>DC brushless</td>
<td>small harmonic drive gear and a high-power mini actuator at each link Bevel gear between actuator and joint</td>
<td>no</td>
<td>Strain Gauges at joints &amp; Force and Tactile sensors at finger tip</td>
<td>Akio Namiki, Yoshiro Imai, Masatoshi Ishikawa, Makoto Kaneko</td>
<td>University of Tokyo, Japan</td>
<td>2004</td>
</tr>
<tr>
<td>25</td>
<td>NAIST Hand [31]</td>
<td>4 (Y)</td>
<td>12</td>
<td>12</td>
<td>DC motors with harmonic drive</td>
<td>Pulleys &amp; timing belt at start before gears placed for moving the linkages</td>
<td>yes</td>
<td>Vision based tactile sensation</td>
<td>Jun Ueda, Yutaka Ishida, Masahiro Kondo, Tsukasa Ogasawara</td>
<td>Nara Inst.of Sci &amp; Tech, Nara Japan</td>
<td>2005</td>
</tr>
<tr>
<td>No.</td>
<td>Hand Name</td>
<td>Model</td>
<td>D o</td>
<td>D c</td>
<td>Actuation Mechanism</td>
<td>Force Sensing</td>
<td>Piezo-film</td>
<td>Author(s)</td>
<td>Institution</td>
<td>Year</td>
<td></td>
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<tr>
<td>26</td>
<td>SDM hand [32] [33]</td>
<td></td>
<td>4(N)</td>
<td>8</td>
<td>pre-stretched, nylon-coated stainless steel cable anchored into the distal link</td>
<td>no</td>
<td>Piezo-film for contact sensor</td>
<td>Aaron M. Dollar and Robert D. Howe</td>
<td>Harvard University, USA</td>
<td>2006</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>RL 1 hand [34]</td>
<td></td>
<td>3(Y)</td>
<td>8</td>
<td>D C Motor</td>
<td>yes</td>
<td>------</td>
<td>Ramiro Cabas, Luis Maria Cabas, Carlos Balaguer</td>
<td>Robotics Lab Universidad Carlos III de Madrid, España</td>
<td>2006</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Cassino LARM Hand [36]</td>
<td></td>
<td>3(N)</td>
<td>9</td>
<td>DC motors</td>
<td>No</td>
<td>force sensing resistor</td>
<td>Marco Ceccarelli</td>
<td>Lab. Of robotics &amp; Mechtronics, Univ. of Cassino, Italy</td>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Southampton Hand [37][100]</td>
<td></td>
<td>5(Y)</td>
<td>15</td>
<td>Electric motors flexorexensor muscle pair</td>
<td>yes</td>
<td>dynamic force sensors fabricated from PZT &amp; temp. sensor</td>
<td>C.M. Light, P.H. Chappell</td>
<td>University of Southampton, UK</td>
<td>2000</td>
<td></td>
</tr>
</tbody>
</table>
2.2.1 Comparison of existing types of MRG

The tabulated information as presented in the table 2.1 clarity of different research work with trend of development till to date can be well observed. The criterion for comparison considered for the study are number of fingers, number of actuators, and number of joints, degree of freedom, and biomimetic approach in design, types of sensors and actuation type. It gives brief introduction of the complete development spectrum in the area of MRG.

From the comparative table 2.1, following observations are detailed for better overview of MRG developments till to date.

1) The mechanisms observed for MRH that causes rotation are vastly different. Basic transmission types used for MRH are of flexible cable and pulleys, rocker arm mechanism, pulleys and sheaths, Spur and worm gear, Tendons and linkages with the center pins....Etc. which belongs to classical group. Where as artificial / air muscles, smart materials ( electro-active actuators ) ...etc are also being used for the selected designs at experimental level.

2) Most of the multifingered hand or gripper seems to have more than three fingers with thumb as an opposing finger.

3) Depending on the end applications the specific designs are made to suffice the purposes. ( e. g. robonaut hand for space- explorations related work , shadow hand for commercial / industrial applications, NAIST hand for human like dexterous hand manipulation, High speed hand for speedy grasping .....etc)

4) In fewer cases the total number of actuator are of same number as that of total DOF required for the operation. Sometimes more number of DOF are also obtained, calling such type of grasping as an underactuated ones. ( being a less number of actuators than DOF )

5) Fabrication methods are from conventional one up-to special method such as the shape deposition method depending on the need of gripping envelope, compactness required for the design, and end task decided.

6) Maximum actuators are obviously electric motors of DC type. Rarely in one / two cases other types are considered.
7) More significant and technically advanced versions of grippers are observed in tune with development of robotisation in the industries (i.e. 1980 onwards).

8) Commercialization of the gripper hand as a regular product in the industrial sector is not observed. Hence academicians/ universities are more involved for the development of robot hand/robot gripper.

9) Combinations of different mechanisms with different actuators are observed on account of need to establish the best suitable combination. The expected design shall need to offer all round performance of gripper similar to human hand.

10) More comprehensive study of special types such as prosthetic hand, high speed hand, Shadow hand, etc. can reveal more specific research areas of applications and more scope for development in to the same as well.

Most of the MRH uses sensors for feedback, and software control systems to organize finger motions for grasping. However, in this thesis, significant efforts have been made to find design a simple enough mechanism which can be easily built and controlled, in order to obtain practical systems particularly in human prosthetics.

Further some relevant papers discussed below gives details helpful for planning and execution of this research work.

L. Biagiotti et. al. [4] has discussed summary of around 14 types of existing multifingered robotic hand in detail. They have considered variety of hands for comparative overview. Okada Hand [4], [5], [30] & [40] is always discussed at the start when discussion opens up in the area of multifingered robot gripper. Okada Hand is using pulleys and sheaths for transmission purpose. Next commonly discussed MRH type is a Stanford/JPL hand (Salisbury and B. Roth 1983) [6]. Presently most sophisticated and advanced types of MRH are Robonaut Hand by NASA, USA and NAIST Hand by Nara Institute of Science & Tech. (NAIST), Japan. [31]

The limitations of early designs, arising mainly due to the cost of the control architecture needed for complex mechanical systems with many sensors and actuators are taken care by reducing the number of degree of freedom (DOF’s), thereby decreasing the number of actuators. In particular, SSL Hand [29], the Grasper hand [14], the Cassino finger [35] [36], and the TBM Hand [25] have followed this path. On the other hand, very
few prototypes involve a smaller number of actuators without decreasing the number of DOFs. This approach is called as 'UNDERACTUATION'. It can be implemented through the use of passive elements like spring or mechanical links leading to mechanical adaptation of the finger to the shape of natural hand.

A paper on development of sensors towards determination of the desired forces to be applied for the non-rigid, delicate or soft surface objects is discussed with support of study of conventional robot systems by S. S. Ohol et. al. [45]. Gripping action, enhanced with the help of sensory system made from combination of tactile sensors with visual interface for accurate, and controlled gripping is found helpful for manipulation of applied forces.

Following are some of the photographs of the multifingered robots which can give exact idea of its overall appearance, performance, utility, end application and scope for variety of applications in different sectors.
Fig. 2.1 Mechanical Hand published by Dix livres de chirurgie [1]

Fig. 2.2 Musician Hand [2]

Fig. 2.3 Okada hand [4], [5], & [40]

Fig. 2.4 Stanford / JPL (Salisbury’s) Hand [6]

Fig. 2.5 Utah / MIT hand [8], [9]

Fig. 2.6 Belgrade Hand [10], [97]
Fig. 2.7 Barret Hand [11]

Fig. 2.8 Ross-Hime Design-Omni hand [4][12]

Fig. 2.9 UB (Univ. of Bologna) Hand II [4][13]

Fig. 2.10 Grasper Hand by North Eastern University [14]

Fig. 2.11 DLR I Hand [4][15]

Fig. 2.12 LMS Hand [16][17]
Fig. 2.13 DIST Hand [4, 18]
Fig. 2.14 Robonaut Hand, NASA [4, 19]
Fig. 2.15 Tokyo Hand [4, 20]
Fig. 2.16 Karlsruhe Dexterous Hand II [21, 22]
Fig. 2.17 Tuat/Karlsruhe Hand [4, 22, 23]
Fig. 2.18 Ultralight Hand Karlsruhe [22, 24]
Fig. 2.19 TBM (Toronto/Bloorview Macmillan) Hand [25]

Fig. 2.20 DLR II (Butterfass, Hirzinger et al.) Hand [26]

Fig. 2.21 Gifu Hand [4],[27]

Fig. 2.22 Shadow Co. Hand [28]

Fig. 2.23 SSL Hand Space Systems Lab.[29]

Fig. 2.24 High-speed 100 g Hand [30]
Fig. 2.25 NAIST (NARA Institute of Science & Technology) dexterous Hand [31]

Fig. 2.26 Fingered SDM Hand, Harvard [32][33]

Fig. 2.27 RL 1 hand [34]

Fig. 2.28 Cassino LARM [35]

Fig. 2.29 Hand Ca.U.M.Ha – Cassino
Underactuated Multifinger Hand [36]

Fig. 2.30 Southampton Hand, [37][100]
It is observed from the above figures that, though prosthesis hand doesn’t come for a discussion while considering MRH for industrial vast applications than only prosthesis purpose. They do possess a sophisticated technology and some of them are available as commercial one as well e.g. Otto Bock [41] , VASI 7-11 [42][95], RTR – II [43] , Otto Bock [41], Southampton [37], Montreal Hand [96] and MANUS hand [44]. For making a complete study of the existing automated hands, Southampton experimental prosthetic hand with adaptive gripping is considered for comparison in above table. To support this, recently developed MANUS hand [ Fig.2. 29 ] also can be observed for in the following figure.

![Fig.2.31 MANUS-HAND, Spain 2004 [ 44 ]](image)

Recently, TBM hand i.e. Toronto / Bloorview MacMilan hand [25] is developed as an experimental prosthetic hand which attempts to increase mechanical functions and cosmetic appearance. It is very close to MRG concept and can be used effectively for robot systems for other than prosthetic purpose with smaller modifications. Hence it is included in the comparative study of existing MRG.

Literature survey made for MRH and MRG focuses a light on the recent trends and efficient designs with biomimetic approach. Biomimetic approach helps designers for the perfection in handling the objects with variety of shape, size and its material phase. Since each hand is developed for different applications their study gives a generalized solution for the effective grasping. Concluding remark after comparative study using table 2.1 information on the page no. 14 gives more wider and detail observations in the area of multifingered gripper. Comparative study does points towards a cumulative
effect of all improved and established technology for developing a simple, low cost, robust, all purpose and biomimetic MRH.

Following is a topic wise study of the referred research papers other than multifingered gripper design. The subsystems of the multifingered robotic gripper are discussed to gain more findings in the respective areas.

2.3 Sensors used for MRG

Sensors for MRG system has been already discussed in the comparative study. It shows that the tactile sensors are the inherent part of MRG and it is but obvious for effective grasping. But while developing the system for universal grasping more innovative sensors and their real time feedback for close loop action is a compulsory stage for the researchers in this area.

A. Bicchi et. al. has done a lot of research in the area of tactile sensation for gripper fingers[46][47]. They have proposed a use of integrated tactile sensors for intrinsic contact sensing for soft fingers. In his later work he has presented a survey in the field of robot hand to propose a minimum use of actuators with simplest set of sensors. He has also proposed distinction is made between hands designed for mimicking the human anatomy and physiology, and hands designed to meet restricted, practical requirements.

Hall effect Sensors by A. M. Dollar et. al. in SDM hand [48]. These include Hall-effect sensors for joint angle sensing, embedded strain gauges for 3 axis force measurements, optical reflectance sensors for tactile sensing, and piezoelectric polymers for contact detection.

A unique design for tactile sensing embedding as many receptors as possible randomly placed in soft material so as to provide different kinds of sensing modalities are presented by Yasunori Tada et. al.[49][50]. The fingertip consists of two silicon rubber layers of different hardness containing two kinds of receptors, strain gauges and PVDF (polyvinylidene fluoride) films distributed randomly as receptors. A PVDF film is expected to sense the strain velocity, which means that it is more sensitive to the transient / small strain (or stick slip) than the strain gauge is. The silicon layer between two PVDF films is
expected to act like a low-pass filter; therefore, the difference between the signals is expected to represent the local stick slip phenomena.

J. Ueda et. al. has designed a new tactile sensor to activate the proposed control method by the NAIST-Hand.[31] This sensor consists of a transparent semispherical gel, an embedded small camera, and a force sensor in order to implement the direct slip margin estimation.

The prototype of the tactile sensor which has $8 \times 8$ array using piezoelectric film was fabricated by Kee-Ho Yu et. al.[51] In the fabrication procedure, the electrode patterns and the common electrode of the thin conductive tape are attached to the both sides of the thin piezoelectric film using conductive adhesive. The sensor is covered with polyester film for insulation and attached to the rubber base for a stable structure. The processed signals of the output of the sensor are visualized in a personal computer, the shape and force distribution of the contact object are obtained. The reasonable performance for the detection of the contact state was verified through the sensing examples.

Jae Son et. al. have experimented for touch and vision sensor that can be used for doing delicate manipulation task [52][53]. Vision provides shape and position at a distance while tactile provides geometric and shape information. They have demonstrated that vision feedback provides rough positioning and tactile feedback and grasp force and orientation can be sensed through tactile sensing.

Starting from the observation of the human hand, L. Biagiotti et. al. have outlined the desirable features of a dexterous robot end-effector, in terms of the manipulation capabilities.[23] The sensing technologies currently available, using force and tactile sensors are the most discussed topic in the field of sensors for robotic manipulation. He has observed that non-contact sensors i.e. camera and proximity sensors explores information at macro level whereas contact type sensors i.e. Force-Torque and tactile sensors offers micro level information.

Even for the rare application such as surgery using MRH, William J. Peine and Robert D. Howe has found that the threshold detection forces increased with ball size and decreased with indentation speed.[54] The shape of the finger and contact pressure distribution on the finger was measured at the threshold force. The relative deformation of
the finger induced by the ball was determined by comparing the shape of the finger indenting models with and without a ball at the same indentation force.

Robert Howe and A. Dollars has contributed a lot in the area of tactile sensation based control with different innovative type of sensors and control strategies [32 ] [33]. Robert Howe & Mark Cutkosky has presented scheme for sensing acceleration of outer skin of manipulator[55]. Humans have similar sensing capability for variety of purposes including differentiating fine surface texture detecting incipient slip of grasped object. They have constructed sensor with thin rubber skin covering soft inner foam layer rubber. An accelerometer attached to inner soft layer measures a large local acceleration as when area of skin catch and snap the surface when it moves on the surface. They have confirmed ability to detect the onset of slip by experimentation

Sensors invention is most rapidly developing area in the field of robotics. Sensors use give perfection to the task. Presently new sensors are available, with better material and real time responses. Smart material like IPMC ( Ionic polymer Metallic Composites ), EMFi ( Electromagnetic film ), Pressurised ink, Nitinol, Nano technology based materials ( lumped mass of carbon nano tubes CNT ), PVDF ( polyvinylidene fluoride) films.....etc. are developed for the sensors. Above discussed paper covers the sensors of following type.

1) Tactile sensors
2) Hall effect sensors
3) Strain gauges and PVDF
4) Semisolid gel like material foe force sensation
5) Piezoelectric material

Even some advanced sensors such as vision system, proximity sensors and accelerometer for the measurement of forces and confirmation of various operation related data are embedded at the fabrication system of the multifingered gripper. This data is correlated and compared for getting the guide lines towards all round experimentation for improvising the grasping capacity.

Vision system is supposed to be the advanced sensory system. Following section discussing the use of vision sensor for grasping action clearly focuses the important
role of such advanced type feedback. It modifies the system towards making the grasping action, based on the real time control and with adaptability in control action for changing situations.

### 2.4 Vision systems for MRG

Use of vision system for Robots remains a challenge to designers, users and academicians. It is almost achieved by newer inventions in the following areas

1) Better Camera for image grabbing, auto focusing, compact size ...etc.
2) Faster data communication for realtime feedback
3) Efficient noise filtering by improved image processing tools
4) Better understanding the data of image by the data analysis softwares.

Hence vision system related work has to be studied for better integration of the vision devices at robotic action. Following are the relevant research papers found in the area of vision system for robotic grasping.

A study on vision based motion planning and exploration algorithms for Mobile Robots which focuses on the problems of designing algorithms that would enable a mobile robot equipped with a visual recognition system is carried out for a systematic exploration of an unfamiliar environment by C. J. Taylor and D. J. Kriegman [56].

Also Krasimir Kolarov [57] has attempted for to find the optimal design of a robot that can reach everywhere in an environment with obstacles without collisions. They have generalized basic problem for the cases when both the robot and the environment are designed simultaneously while dealing with moving robots and obstacles as well as multiple robots or robots with variable structure.

Zhongming Lian [58] has used monochrome CCD camera with video monitor and frame grabber software for teaching robot vision in Manufacturing Technology.
Integration of touch and vision for delicate manipulation tasks is experimented by Jae S. Son, Robert Howe et. Al. [52] They demonstrated visual sensor feedback for rough positioning and tactile sensor feedback for grasp force and object orientation sensation. They have observed that the use of tactile sensing results in a much more gentle grasp. Use of tactile array sensors which consists of grids of pressure sensors at gripper pads is used to provide contact location and contact force information.

Calibration of an anthropomorphic two armed robot equipped with a stereo camera vision system that is estimating the different geometric relationships involved in the model of the robot has been presented by Christopher Garcia [59]. Two algorithms are developed, first implementing a non-linear optimization method using quaternions for camera calibration and second one with a real time camera pose estimation method based on the iterative use of a para-perspective camera model.

Kevin Stanley et. al. has described the implementation of a vision based algorithm that is capable of rapidly determining robotic grasp points for planar objects.[60] The proposed algorithm evaluates points on the boundary of the object and progressively refines the search until a grasp is found. The grasp planner finds feasible grasp points that are collision free and stable.

A direct visual servoing system was described which employs a network cameras providing high speed vision feedback and it is further applied to the direct visual servoing of a planar robot by Derek C. Schuurman [61].

Industrial robots using 2D vision system for manipulating a 3D object on the surface without inaccuracy is suggested in the study of Frank S. Cheng. And Andrew Denman [62] They have suggested vision guided industrial robot applications which relies on developing a robot programme that is able to initiate vision offset value in robot operations apply it to motion command for moving the robot for gripper action position.

A multifingered robot hand named as ‘NAIST Hand’ is presented by Jun Ueda et. al. [31] for achieving human-like dexterity. This hand has three finger and an apposing thumb. A vision-based tactile fingertip sensor is also developed to implement the direct estimation algorithm of the slip margin.
This all available papers present the technology of using 2D and 3D camera for robot systems. The use of such system is meant for advanced / critical type of application. Hence cost and control of such grippers are away from the real life control and affordable cost. Robotisation has got spread over large variety of part handling where application requires user friendly and cost effective implementation of vision systems. Issues like automatic focusing of the camera lenses, Image processing with filtration of the noise, correct placing of the camera w.r.t. the grasping position of the MRG ……etc are considered seriously and guidelines were taken from the available research work in this area.

While using all the types of advanced sensors with better control action at the stage of the planning one has to decide that whether mechanical design and the selected mechanism is worth for the decided action. Hence Modeling and simulations implemented for the other MRG or robot functions are covered by the literature survey completed in this area, as presented in next section.

2.5 Modeling & Simulations of robot gripper

Modeling and simulation at various level offers virtual platform to experiment with the actual design. It has many advantages such as

1. It is useful to detect interferences within the components, thus it allows for modifying the dimensions of components prior to the manufacturing.

2. It is possible to modify the components to control the parameters such as weight and shape of each element and role of each element at motion.

3. It is possible to analyse the motion of components relative to each other.

4. It is possible to change the relative alignment and orientation of the various elements of the system.

Following are the findings from the relevant research papers in the area of modeling and simulation of MRG.
A novel modeling framework for the multifingered manipulation with finger gaits is proposed by Jijie Xu and Zexiang Li [63]. Through classifying the fingers into grasping fingers and free fingers, an alternate representation of a grasp is introduced by them. With the consideration of both its discrete and continuous characteristics, the kinematics model of a -fingered manipulation with finger gaits is formulated into a hybrid automation. Finally, simulation results are used for verifying the validity of the proposed modeling framework.

Mobile robots are widely utilized for various operations in environments inaccessible to a human or dangerous for him. The work done by Sergey F. Jatsun et al. discusses a new concepts of motion to enable robots to move efficiently in environments inaccessible to robots with wheel, caterpillar, and walking propelling systems [64]. Such types are often discussed for medical robots designed for the drug delivery by a motion through rather narrow channels to reach an affected organ to perform a diagnostic or surgical operation.

Gianni Borghesan et al. in their paper has discussed, two problems related to the simulation of virtual environments for haptic systems [65]. The first problem is how to simulate, in discrete time and with low computational effort, dynamic systems in order to preserve their passivity properties. The second problem discussed in this paper is the interconnection of algorithms running at different frequencies, i.e. the control algorithm of the haptic interface (running typically at high frequency) and the algorithm simulating the virtual environment (running at lower frequency). A proper software interface, able to connect these two algorithms in an energetic-consistent manner, is presented and discussed. Such type of interactive control is helpful for the integration mode of the subsystems of MRG.

Simulation is used for the identification of design problems. The work planned and result related to design of a robot system for joining ship sections are described by Mikael Fridenfalk et al. [66]. They have applied simulation and a virtual prototyping method, in the design process of a robot system for arc-welding of ship hulls. Virtual design of a robot system using simulation tools such as Envision TR 2 is successfully practiced by them. A discussion of further steps such as systems description of the robot system with information of the application area specification is discussed. They have emphasized that
simulation of the system including the sensor interaction and tolerances is an important part to validate the robustness of the design.

The use of theory of impulse and momentum is suggested by Kalyan K. Mankala and Sunil K. Agrawal [67] to model different operating phases of motion of the tether-net/gripper system. They have proposed that the dynamics of the motion of the system can be characterized by differential and algebraic equations (DAEs). Also Matlab ODE solvers were used by them to solve these DAEs.

Kinga Stasik [68] has presented a pinch type gripper for handling fabrics in textile industries. A mathematical model is presented by him, which takes care of unwanted high pressure rise due to very small point like surface contact by the gripper with the fabrics. An equation developed by him describes the computer programme simulating the gripper.

A number of mobile robot simulation systems are developed by Andreas Koestler. [69] He has stated that it has been found that all previous simulators had in common with the "EyeSim" simulator presented in their current research, is the duplication of a real robot's API (application programmer interface), the simulation of all its sensors and actuators, adjustable error models, and the generation of a virtual camera image that can be fed back into the application program. This declaration highlights that for structured gripping with skill, such as precise grasp and complex gripping operations the above mentioned strategies can be used.

The research by Joseph T. Wunderlich provides a means of rapid-prototyping robotic arms for enclosed spaces and which can yield many designs locally optimized for given tasks and environments [70]. He has presented a simulation for designing redundant robotic arms for enclosed spaces by permuting link lengths and DOF. Further comparing feasible designs for maximum simulated speed and dexterity and minimum joint-angle displacement, DOF, the consumption of available redundancy is evaluated using a newly developed measure over test trajectories.

A complete mathematical model of SCARA robot (Serpent 1) is developed by Yuru Zhang and William A. Gruver [71] including servo actuator dynamics and
presented together with dynamic simulation. Using Lagrangian mechanics they have derived the equations of motion relating joint torques, positions, velocities and accelerations. Some simplifying assumptions like; no gear and transmission losses and friction in joints are taken while deriving equations of motion. D.C. servomotors driving each robot joint is studied with PD controller action. Serpent I robot is instructed to achieve pick and place operations of three different size cylindrical objects through assigned holes. The performance of robot-actuator-control system is examined with numerical simulation and experimentally verified.

The influence of size and material properties of fingertips on the power-law equation for soft finger contacts has been investigated by Nicholas Xydas and Imin Kao [72]. The normal and tangential stiffness of soft materials have been experimentally investigated in order to demonstrate their suitability with the development of compliant pads for robotic hands by L. Biagiotti et. al. [73]

A kinematic model of a piezo actuated biologically inspired microgripper design is proposed and a dynamic model based on Euler-Lagrangian approach is developed by Lionel Birglen, Clement M. Gosselin [74] considering the system as combination of mass-spring-damper. The mathematical model is then simulated using MATLAB/SIMULINK.

They have worked to establish a fundamental basis for the analysis of underactuated fingers with a general approach. The suggested method is based on the introduction of two new matrices, which explains the relationship between the input torque of the finger actuator(s) and the contact forces on the phalanges. Using this method, the conditions under which certain phalanx forces vanishes, can be studied. It can be completed along with comparison of different under actuation mechanisms. [74]

The simulator using IPC (Inter Process Communication) library based on TCP/IP is observed by Abdul Ghafoor, Jian S. Dai, Joseph Duffy [75] It consists of the four units: communication, robot control, kinematic design, and driver for real robot operation. Implemented in the simulator are seven kinds of URC robots. By providing only the link parameters, a new robot can be added. Also, a user can generate a working environment consisting of walls. The real robots and virtual robots can operate in parallel.
is used for verification of collision avoidance algorithms in an environment with multiple heterogeneous robots.

A dynamic simulation package has been developed by M. Taylan Das, L. Canan Dülger [76], which can accurately model the interactions between robots and their environment. It creates a virtual environment in which various controllers and work cells can be tested. The simulator is divided into two parts: local objects that compute their dynamic equations of motion and a global coordinator that resolves interactive forces between objects. This simulator builds upon previous work on dynamic simulation of simple rigid bodies and extends it to correctly model and efficiently compute the dynamics of multi-link robots.

A kinematics’ model of a piezo actuated micro gripper design is proposed and a dynamic model based on Euler – Lagrangian approach is developed considering the system as a mass – spring – damper by Madhab G.B., Kumar C.S., Mishra P.K. [77]. They have also discussed and design of such two fingered microgripper actuated by a pair of agonist and antagonist piezoelectric multilayer stack actuators. They have used genetic algorithm based approach for optimization of gripping forces.

As per the advantages stated at the start of this topic it is very much understood that simulation are the unavoidable stages at design of the system and they reduces total time period and actual efforts of the involved individuals, marginally. This process presently offers more user friendly and visual output on account of availability of more efficient software.

At the stage of finalizing the virtually tested designs of the systems the care has been taken for making MRG a more appropriate biomimetic version in reference with the task statement. Biomimetic approach is applied for robot gripper by maximum number of the peoples involved in this study because they do believe on achieving the best solution closer to human hand for designing the universal griasper. Following section discusses the adopted biomimetic approach by the various researchers in the allied area of robotized gripping.
2.6 Biomimetic Design Approach

Biomimetic Science has been evolved recently. It is contributing significantly, almost in every field of research. Inspired by the nature and adopting the concepts established by the nature helping the innovators to achieve the best designs. Currently many researchers are actively working on developing universal gripping system with dexterous material handling by implementing biomimetic approach in the grasping operations. Following are the selected research works in the robotic grasping. It focuses a light on the utility of biomimetic approach and various concepts evolved on account of its implementation.

The design concepts discussed by T. Mouri and H. Kawasaki while developing Gifu Hand, [78] narrates towards biomimetic approach. Issues related to the use of tendon / cables for gripping actions are discussed in this study. Also remedy is provided by using the linkages for mechanical grasping.

Another similar effort by making provision of multimodal sensors placed on / in a soft surface of the tip of the gripper finger is made by Y. Tada et. al. [79] They have proposed a design for tactile sensing to embed as many receptors as possible randomly in soft material so as to provide different kinds of sensing modalities. The fingertip has two layers of different hardness with two kinds of receptors randomly distributed i.e. strain gauges and PVDF films. Discrimination of hard surfaces are confirmed by this gripping system.

It is emphasized that an anthropomorphic term associated with grasping phenomenon is expected for the gripper with versatility and human like approach. In a study by J. L. Bank.[80] feedback about the content of its surroundings is suggested in order to exhibit flexibility for embedding adaptability in the system. To impart the qualities of human action to the robot which enable adaptability, the incorporation of active, multi-point sensation is experimented. Internally generated as well as externally imposed contact forces to the system are offering dynamic presentation of the gripper system.
Chapter 2 Literature Review

A paper by G S Gupta et. al. provides the information on the design and development of a low-cost control rig to intuitively manipulate an anthropomorphic robotic arm using a bilateral master–slave control methodology.[81] It is a similar attempt for achieving biomimetic gripping action with real time sensory feedback based control action.

Further patterns of hand motion during grasping and the influence of sensory guidance is experimented by M Santello et. al. [82]. This widens the scope of biomimetic action analysis by experimenting for grasping with the conditions such as, the memory guided movements, virtual imagination and physical object handling, with the help of 15 DOF hand.

Biorobotics is another term which also reflect the similar logic for total robotic action with robot gripper as a subset. Associated parameters like Hand kinematics, Finger joint actuators, Drive chain components, Number and location of sensors are discussed with biomechanical design strategies by J N Marcincin et. al.[83]

For initial and final conditions of grasping, human unconsciously changes the grasp strategy according to the size of object even if they posses same geometry. It is termed as the grasp planning for the scale dependent grasp. The grasp patterns thus observed in human grasping are applied with couple of grasp procedures to multi-fingered robot hands by T. Shirai et. al.[84]. In this study a sliding based grip and a rolling based grip with four different patterns are suggested for multifingered Robot hand on the basis of study of human hand grasping.

A concept for integrating the control system of an anthropomorphic robot hand into the control system of an entire humanoid robot was presented by D. Osswald [85]. A grasp taxonomy was developed on the basis of the objects and actions in the intended environment that can be used to describe the grasp patterns required for robot gripping. The architectures of the overall control system and of the superior and local hand control system in particular is presented. This once again emphasizes the need of biomimetic design approach at the control as well.

It is interesting that A Dollar has worked out for the study of the effect of load carrying on the speed of locomotion in arthropods and a biomimetic arthropod robot.
This type of biomimetic study from living animals and creatures is found equally helpful for understanding creativity of nature as per the need for the living being.\[86\] \[87\] This extensive review helps to get different view points of the researchers in the area of biomimetic studies. Further this motivates and guides for transforming the observations into the mechanisms or the working models.

Biomimetic approach at design becomes essential when the design of prosthetic hand for automatic functions is discussed. Control philosophy for a simulated prosthetic hand is detailed by T. Iberall et. al.\[88\]. Using one (Multifingered Robot Hand) MRH as a prototype prosthetic hand in order to evaluate a system that translates task-level commands into motor commands is experimented by them in virtual environment.

Multifingered mechanical hands are attempts at approximating human hand functionality which is also highly developed discipline directly related to the designs of the sophisticated prosthetic hand. Oxford and Manus prostheses hand are compared by P. J. Kyberd and J. L. Pons \[89\]. This paper focuses a light on the current trends in the research on the prosthesis and study of aspects related to mechanical design, sensors and manipulation schemes.

Attempts towards making MRG similar to human hand for automatically gaining human hand advantages is stated in above works. To design a universal grasping system biomimetic approach is observed in most of the above discussed research work. The recent trend as depicted in the various attempts as per the above mentioned studies clearly indicates that biomimetic approach is essential for improving the grasping modality of the robot gripper. Accordingly multifingered hand and gripper are designed and controlled successfully.

After selection of the mechanism, sensors, actuators....etc for MRG and observing the simulation results, Analytical work in determining the required gripping force for perfect grasp remains as a priority step in the process of design of MRG. Kinetostatic analysis and gripper force related research work’s literature survey is made as per the following details.
2.7 Gripper Forces Determination and Kinetostatic analysis

Grippers are to be designed for safe working. There static and dynamic analysis is to be completed for the confirmation of its better performance at operating condition. Following are the fewer selected papers in the area of robotized gripper. These are proved to be the frame of reference for the various stages of design.

A. Bicchi and V. Kumar made a survey of the work in robotic grasping a related area that has been covered for almost last twenty years towards the development of theoretical and analytical work in this area. They have also discussed some of the key problems faced by researchers in this area.[90]

E. Staffetti has presented a novel frame for studying the statics & the instantaneous kinematics of robot manipulators based on the Grassmann–Cayley algebra. The study reveals that the Grassmann–Cayley algebra permits us to work at symbolic level, that is, in a coordinate-free manner, and to obtain closed-form expressions of the twist and wrench spaces of robot manipulators. [91]

T. Maeno and others, to estimate the friction coefficient between a planar surface and an elastic finger-shaped sensor by only pressing a sensor against the surface of an object, propose another relevant method. They considered contact condition between a planar surface and a half-cylindrical finger for finite-element analysis. The deformation of the elastic finger, contact forces, and strain distribution inside the elastic finger are calculated for various friction coefficients between the finger & the surface. This approach is referred for the planned work. [92]

A multifingered robotic hand named eNAIST-Hand is introduced with a grip force control by slip margin feedback. The NAIST- hand has a new mechanism by which all 3 motors are placed inside the palm without using wire-driven mechanisms. [93] A method of grip force control is proposed using incipient slip estimation. A new tactile sensor is also designed to active the proposed control method by the NAIST-Hand. [31].
L. Birglen and C. M. Gosselin has presented and analyzed the force capabilities of underactuated fingers. The focus of his work is the introduction of matrices (Jacobian) and (Transmission). These matrices allow immediate characterization of the finger, provide the expressions of contact forces developed by the finger, lead to considerations on equilibrium with any number of phalanges in contact, and provide tools for comparison between different designs. Such comparisons can be very useful to choose a particular design of underactuated finger. [74] This paper is also discussed for the model it has presented in the section 2.5 of this chapter.

J. Ueda and T. Yoshikawa has presented the mode-shape compensator which modifies the dynamics of the rigid body so that the vibration mode is shaped. [94] It is stated that as a result of this mode shaping, the robustness is improved. It is necessary to examine how much the manipulability of the rigid body changes at the operating condition. The compensator suggested by them consists of a constant gain matrix and acceleration of each joint. The structure is simple and easy to use. The design method for this mode-shaping matrix is presented in this work.

Finger gait is necessarily needed in order to relocate fingers of the robotic hand when a dextrous manipulation task cannot be accomplished only by the rolling and sliding motions of the fingers. The work by J. Xu and Z. Li provides a new modeling method for the manipulation involving finger gaits [63]. By viewing the -fingered manipulation as an entire system, both constraints of individual fingers and requirements for the multifingered manipulations are considered. Since the fingers have different roles in different modes of manipulations, they are classified into two types, grasping fingers and free fingers. An alternate representation of grasp, which takes both types of fingers into account, is further introduced. This is also referred for the section 2.5 of this same chapter.

Various issues discussed in the above relevant research papers are design perfections for appropriate grasping force, contact deformations, finger posture at grasping by applying optimum forces, deciding the role of each element of gripper system at various modes of manipulations...etc clears the precautionary measures at the design stage.

Next area considered for literature survey is controlling and system programming and controlling. Though control algorithm was finalized initially, it has been refined and found more effective for the planned task by the MRG system. Therefore the
various aspects of the relevant and selected work for controlling the MRG are presented below with its brief discussions on the findings.

### 2.8 Controlling and System Programming

Controlling the system with best programming by hardware arrangements and use of efficient softwares helps the system to work more precisely as per the requirement. Both the processes are parallel and hence discussed together for the literature referencing. The issues related to this such as real time control, users access at various modes for alteration, scope for future developments, and economical frame can be well controlled by the effective programming and real time control with closed loop action. Following are the few relevant selected papers in this concern.

Robert D. Howe and Mark R. Custkosky [55] has described how to use tactile sensing for in the control of robotic manipulation. they have analysed kind of information that can be derived for each type of sensor and their use in dexterous control. They have also described architecture of flexible controller that use the tactile information during task execution to adjust the control mode as system changes the state.

J. Ueda and others, based on a visual slip-margin feedback, propose a grip-force control of an elastic object [93]. They have stated that, when an elastic object is pressed and slid slightly on a rigid plate, a partial slip, called “incipient slip,” occurs on the contact surface. The slip margin between an elastic object and a rigid plate is estimated based on the analytic solution of a Hertzian contact model. The slip margin between an elastic object and a rigid plate is estimated based on the analytic solution of a Hertzian contact model. A one-degree-of-freedom gripper consisting of a camera and a force sensor is developed. The slip margin has been estimated from the tangential force measured by a force sensor, the deformation of the elastic object and the radius on the contact area both measured by a camera.

Peter Deckers, Aaron M. Dollar, and Robert D. Howe [99] describes the application of a partially observed Markov decision process (POMDP) to guide the control decisions made during the task of grasping objects with a simple compliant grasper in unstructured environments. The decision process relies only on the sensing of angular
deflection of the compliant gripper joints – proprioceptive information available on most robot hands and grippers. This information is used to infer the state of contact between the gripper and the object and guide a set of actions to be undertaken in order to lead to a successful grasp. It is believed that the performance of the gripper under a POMDP model built from this limited sensory information will serve as a valuable baseline for comparison with more complex sensing modalities, allowing for quantitative analysis of the tradeoffs between commonly available sensory suites.

Issues related to the description of end-effector tasks that involve constrained motion and active force control are discussed in the paper of Oussama Khatib [101]. The fundamentals of the operational space formulation are then presented, and the unified approach for motion and force control is developed. The extension of this formulation to redundant manipulator systems is also presented, constructing the end-effector equations of motion and describing their behavior with respect to joint forces.

It is stated by Dirk Osswald and Heinz Worn that to perform dexterous fine manipulations with a robot hand a suitable mechanical system and control system is necessary [102]. The Karlsruhe Dexterous Hand II is planned for fine manipulation with an adaptable type of system. The special kinematic abilities of such a robot hand, like small masses and inertia, make even complex manipulations and very fine manipulations of a grasped object within the own workspace of the hand are possible. Difficult movement like regrasping is also achieved successfully.

The design and augmented capability of a robot hand using a set of additional sensors are discussed by Peter K. Allen et. al. towards integrating the system for grasping with vision, Force and Tactile sensors. They have experimented for the grasping task which requires closed loop and real time control. The similar approach is adapted by the present work and series of experiments and different sensors with refined logical control is attempted in it [103].

Robert D. Howe and Mark R. Cutkosky developed an architecture for a flexible controller which uses the tactile information during task execution to adjust the control mode as the state of system changes [104]. In this work they have reviewed sensing technologies and outlined an approach in which the information from tactile arrays, force
torque sensors, joint angle sensors and dynamic tactile sensors are combined to detect the changes in contact conditions and overall grasps.

Robert D Howe et. al. have suggested that the sensors and the fingertips must be designed so that they reliably report only the changes in the contact status and motion of the object.[105]. They have experimented for such type of control action and emphasized that tactile and force sensors can contribute to smoothness and flexibility in robotic grasping.

The outcome of the literature survey is embedded at various stages and as per their appearance and availability. Though the scope of the presented work is wider, only relevant papers are selected to save the effort and time. This decision has helped and proved effective to obtain various inputs in this work at various stages.

It is important to study the recent developments in the allied area of research. It is equally important to study the basic theory and concepts established in the various discipline related to MRG. Hence, the theory concerned with the MRG developments (e.g. anatomical study of human hand and the grasper designs .. etc.) is presented in detail to understand the further newer developments.