REQUIREMENTS OF NEXT GENERATION ROBOTIC MANIPULATORS

M. Culleton, K. Kelly

Department of Mechanical and Manufacturing Engineering, Trinity College, Dublin 2, Ireland.

ABSTRACT

Recent projections suggest that there will be considerable growth in coming years in the area of assistive robotics, in both domestic and industrial scenarios [1]. An important enabler of this is likely to be the development of flexible, multi-purpose grippers/manipulators. This paper explores key challenges in the development of such manipulators, including manipulator design and implementation, control algorithms, manipulation strategies, and human-robot interaction, and identifies a roadmap to the successful deployment of next generation systems.

KEYWORDS: Robotic Manipulators, Human-Robot Interaction

1. INTRODUCTION

The use of robots in industry initially developed in the automotive sector, where automated robots became a part of the assembly process. This began in 1961 with 'UNIMATE', the first fully automated robot used by General Motors as an automated die casting mould which quenched molten steel into the various automobile parts required for production.[2]

Since then robotics has expanded into a large variety of sectors, including the manufacturing, medical, space, and domestic sectors. This is, in part at least, attributable to the advantages of using robots in completing repetitive, dangerous and/or high accuracy tasks. More recently, there has been a shift towards assistive robotics [1] to aid and empower people during their daily lives – both working and domestic. In domestic environments this allows people greater independence and quality of life, while in the working environment robots can now function within human workspaces in a safe and interactive manner. This allows for the combination of complementary skillsets; human intelligence and dexterity with robotic precision and productivity.

This paper will focus on the development in assistive robotics with regards to robotic manipulators. The paper will discuss a range of manipulators currently available along with those being developed with a focus on human assistance. Throughout the discussion the functionality, features, and benefits of each manipulator design will be highlighted.

Subsequently, the control algorithms and strategies currently utilised by manipulators will be explored. This will include gripping and manipulation strategies, as well as more specific control strategies such as those tailored for interaction with humans.

Developing from this, human-robot interaction will be discussed. This will include the safety features and strategies incorporated in manipulator design, as human safety is of primary concern.

Combining the above observations and findings, a number of requirements for next generation manipulators will be established. These will aid in the development of assistive robotics, allowing robotic manipulators to undertake more advanced, collaborative tasks.

2. MANIPULATORS DEVELOPMENT

Thanks to funding initiatives such as the National Robotics Initiative and DARPA, there has been significant development of robotic manipulators over recent years. This coupled with advances in available technology, such as lower cost actuators and circuitry, has driven some researchers to develop robotic manipulators with similar capabilities to that of the human hand. In order to achieve this feat, manipulators must match the human hand in terms of power, speed, and dexterity.

2.1 Manipulator Power

Since their introduction, robotic manipulators have easily been able to surpass the power capabilities of the human hand by use of high torque motors and pneumatic actuators. However as robotics moves towards a more mobile platform, weight is now an issue which has led to the power-to-weight ratio becoming an influential design consideration. This has led to the development of new advanced actuators such as ‘Smart Motors’ and ‘Air Muscles’[3].

These actuators are typically connected to the joints of the manipulator either by a gear array or by wire tendons. Geared systems create a secure link between actuator and limb, which has been found to be advantageous for power grasps and manipulation [4], [5]. However due to growing significance of minimising weight, recent years have seen a shift towards the use of wire tendons. This is of additional advantage in robotics as it removes the actuator from the point of motion, allowing the manipulator to match the size and weight of a human hand. The external location also removes the limitation on the number of actuators, which means that wire tendon driven manipulators can more easily match the Degrees of Freedom (DOF) of the human hand e.g. The Shadow Dextrous Hand C6M, which has 20 DOF [6]. As well as this, the freed space within the hand allows for feedback sensors to be more easily integrated, which allows for force controlled grasping as shown in Figure 2.1.

Figure 2.1: Shadow Dexterous Hand C6M [3]

While the location of the external actuators can vary, many are housed within an arm which has led to full hand-arm systems often being developed. Some of the most advanced of these include the DLR hand-arm system and Robonaut 2 [7],[8]. The latter, which was developed by NASA, has been designed to assist astronauts with servicing tasks while in space. This development of assistive robots is seen to be of significant benefit in terms of task productivity, accuracy, and quality.

With specific reference to the hand, Robonaut 2 has sufficient power to grasp various objects and preform standard tasks (Figure 2.2 and Figure 2.3). By modelling the manipulator on the human hand, Robonaut 2 can use everyday tools and equipment, meaning modification of the environment is not required.

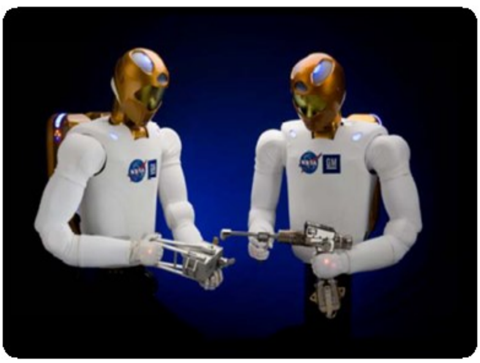

Figure 2.2: NASA Robonaut 2 [8]

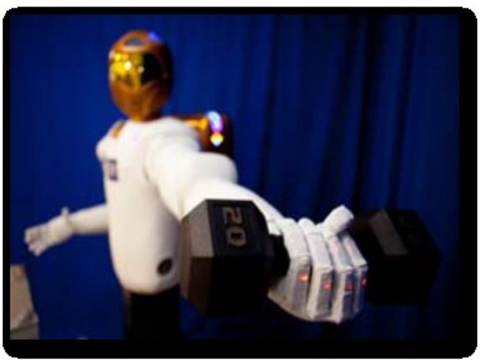

Figure 2.3: Lifting Capability of Robonaut 2 [8]

2.2 Manipulator Speed

When undertaking predetermined repetitive tasks, robotic manipulators excel in terms of completion rate and efficiency. However, these are specialised robots which are very limited in terms of versatility. As current trends require robots with more flexible and assistive capabilities [1], manipulators are now being designed to perform a range of movements, comparable to those obtainable by the human hand.

A number of robotic manipulators have been developed which now match if not exceed the speed capabilities of the human hand. Some examples include the Barrett Hand, Keio Hand and the University of Tokyo Hand [9]. The latter is a high speed motion manipulator, which can perform a range of motions at speeds 15x faster than that of the human hand (Figure 2.4) [10].

Figure 2.4: University of Tokyo Hand [10]

2.3 Manipulator Dexterity

At present, dexterity is the key area in which robotic manipulators fall short. According to the recent edition of ‘A Roadmap for U.S. Robotics’, this is mainly down to gaps in key technology areas, such as perception, robust high fidelity sensing and planning and control [1]. In an attempt to overcome these technological gaps, unique designs such as the Anatomically Correct Testbed (ACT) Hand have been developed.

The ACT Hand, shown in Figure 2.5, is biomechanically designed to resemble the anatomy of the human hand, including bone structure and tendon arrangements, and is controlled by software based on the body’s neuromuscular control system. [9] At present the ACT Hand is being used to gain a better understanding of the human hand, which will be of benefit in the future for developing more dexterous and functional robotic manipulators.

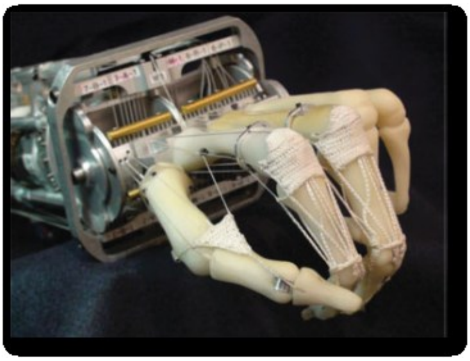

Figure 2.5: The ACT Hand [9]

2.4 Prosthetic Arms

In terms of assistive robotics, prosthetic arms have been a crucial development in providing users with self-independence. However until recently they were designed for very basic grasping and manipulation, which can be seen from the most widely used two-fingered hook prosthesis [11].

However, recent funding initiatives such as the DARPA ‘Revolutionizing Prosthetics’ program launched in 2006 has drastically improved the functionality of prosthetic arms. One such arm is the DEKA Gen-3 arm system, which provides the user with 10 DOF using a foot based controller (Figure 2.6).

Another DARPA funded project is the APL arm system developed by the Johns Hopkins University Applied Physics Lab. This arm system has 22 DOF and is controlled using electromyography (EMG) technology, meaning that movement of the hand and arm is achieved by recording and decoding the neural signals sent from the brain [12]. This is currently achieved using surface electrodes, but trials are already beginning to control the arm using electrode implants. With reference to other papers, it is clear that EMG technology is a potential and favourable solution to controlling prosthetic arms [13] [14].

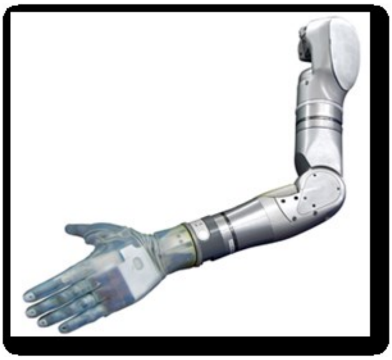

Figure 2.6: DEKA Gen-3 Arm System [15]

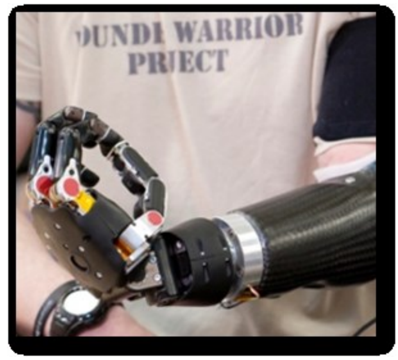

Figure 2.7: APL Arm System [12]

3. MANIPULATOR CONTROL STRATEGIES

According to H. Liu, the advancement of manipulator control over recent years can be attributed to the addressing of three important engineering challenges: [16]

1) Optimal manipulation synthesis problem
2) Coordinated manipulation with finger gating
3) Real-time grasping force optimisation problem

These challenges stem from the recent drive for more flexible and dexterous robots, as previously mentioned. A consequence to this transition is that control strategies and mathematical models previously used for specified movements are becoming inadequate. For example, previous robotic arms were typically designed with up to 6 DOF as the kinematics and computational analysis for such systems are well defined [17]. However recent improvements to dexterity and task space motion have resulted in the introduction of higher DOF arm systems. These require more advanced mathematical modelling and control strategies, such as those used to control the 7 DOF redundant manipulator with offset wrist [17].

With changing trends, robotic arms are more commonly faced with the manipulation of unknown objects. This requirement has led to the development of versatile control strategies with regards to detection and identification of target objects [18–20]. Mimicking the human body, many researchers have achieved this using vision based systems to capture and process the robots surrounding environment [21], [22]. One such system uses a process known as interactive singulation in order to detect and remove individual objects from a pile [23]. This is achieved using local features and transform equations to determine if a single rigid motion explains the new state (Figure 3.1).

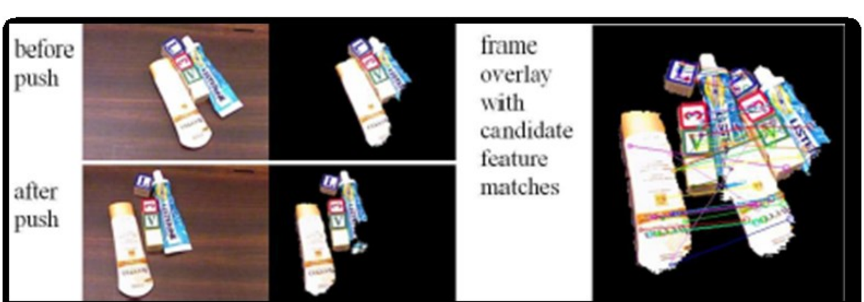

Figure 3.1: Interactive Singulation of an Object from a Pile [23]

The above example of interactive singulation is also of interest as it highlights the requirement for real-time decision making in modern robotic systems. This is a key development area as real-time processing allows the system to react and adjust to a changing environment. The changing environment may occur at the interface of the robotic manipulator and object, or within the task space of the robotic arm. This has led to the development of control systems capable of reacting to deformable object surfaces [24] and assessing grasp stability during object contact [25].

4. HUMAN-ROBOT INTERACTION

With manufacturing transitioning into a more flexible and adaptive field, it is envisaged that humans and robots will share the same workspace [26]. This has driven the development of human-robot interaction, an area which incorporates the real-time control strategies mentioned previously. These are paramount in order to allow manipulators to react to their surrounding environment and ensure the safety of human co-workers during interaction. The importance of this can be seen in recent publications, which address topics such as collision detection and human centred motion planning methods [27–29].

Building from these control strategies, robotic systems have been developed which can predict human motion based on incipient movements [30]. This is advantageous in shared human-robot workspaces, as it allows the manipulator to take preventive actions in potentially dangerous scenarios. This was explored in [30], where a new control strategy was developed to predict human motion using artificial neural networks and previous pattern of motion.

Equally, manipulator motion can be altered to allow for anticipation by humans. One research team achieved this using the Rapid Upper Limb Assessment (RULA) criterion. This scoring system helps to determine which of the manipulator's potential poses resembles that of a human (Figure 4.1) [31]. By limiting the manipulator's motion to these poses, human-robot interaction is aided since the human co-worker can anticipate and react to the robot's motion.

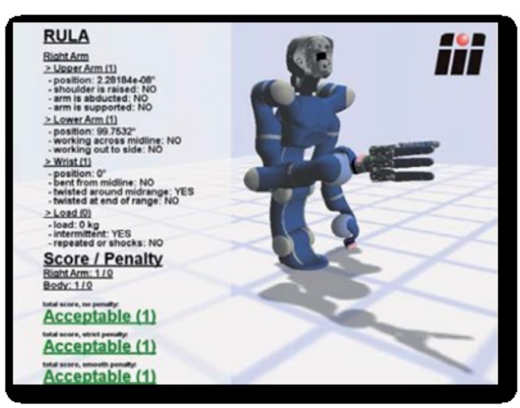

Figure 4.1: Using the RULA Evaluation Criterion to Determine Natural Poses [31]

Another key area of research in the area of human-robot interaction is the physical interaction between the two. In [27], a robotic manipulator has been designed for easy and continually safe operation by non-trained workers. For those that work collaboratively with humans, a method has also been developed to improve the physical handover between robot and human [32]. This method ensures the most appropriate part of the object is orientated towards the human, which in turn ensures a safer and more comfortable transition.

5. NEXT GENERATION SYSTEMS

As mentioned within this paper, robotic manipulators are beginning to emerge with more flexible and assistive capabilities. A key area to the continued success of this is the improvement of manipulator dexterity. Presently, robotic hands fall far behind human hands in terms of dexterity due to gaps in technology such as perception, sensing, planning and control [1]. However with the research and funding currently present in these areas, this gap can only diminish. According to 'A Roadmap for U.S Robotics', it is anticipated that within the next fifteen years we will see the development of high-complexity hands capable of whole-hand grasp acquisition and dexterous manipulation of objects found in manufacturing environments [1].

This predicted functionality would allow robotic manipulators to assist in flexible manufacturing. To achieve the short product cycles, assembly adaptability and precision required for this, human-robot teams could be introduced whereby the strengths of both are utilised to improve overall productivity. Before this can occur, human-robot interaction needs further development in order to ensure the continual safety of the human workers. This will require further development of the control strategies, motion planning, and physical interaction discussed in the preceding section. Once achieved, robotic manipulators will be capable of detecting, anticipating, and interacting with humans in a safe manner. This will initially commence within constrained environments, but as the manipulator's vision and object detection improves this constraint can be removed.

Another area which will assist in the adoption of human-robot teams will be the development of light weight manipulators. Present industrial robots are designed with a large inertia to facilitate heavy lifting and manipulation. This coupled with their high speed motion makes them inherently dangerous to humans, which is why safety barriers are currently used. However the move towards lightweight materials and motors could reduce the body mass of future manipulators, [26] which would reduce their potential risk to humans and allow for their operation within human workspaces.

To assimilate within flexible manufacturing, it is important that future manipulators are easily and rapidly programmable to allow them to react to changing product cycles. To remove the requirement for specialised training, solutions such as adaptive teaching methods are being developed [26]. These methods allow factory operators to easily program the robotic manipulator by guiding the manipulator along the required path. Using torque/force control sensors at each joint, the manipulator can record its start point, end point, and intermediate path in order to replicate the desired motion. [26] While in its infant stage, adaptive teaching has the potential to be developed and incorporated into next generation manipulators. However this will require a shift towards a more common programming language, as most robotic manufactures presently use their own high level language [26].

Next generation manipulators will also be adopted in the domestic sector thanks to a rapid growth in assistive robotics use (over 20% annual increase within the USA) [1]. For this to occur, similar challenges to those in manufacturing need to be overcome. Detection and interaction capabilities are crucial, which will require the development of perception, sensing, and motion planning, as discussed above.

Finally, additional technology could be integrated into robotic manipulators in order to achieve a performance unobtainable by humans. A current example is the SRI International Electroadhesion Gripper, which strives to achieve a more stable grasp by use of electroadhesion technology [33]. This is achieved by implanting electrodes within the end effector to generates electrostatic forces between the gripper and object [33]. Such a technology could be included in next generation manipulators, which would allow them to surpass human hand capabilities in terms of grasping and manipulation.

6. CONCLUSIONS

To meet future requirements in sectors such as manufacturing and the domestic sector, it is important to develop more flexible, multi-purpose grippers/manipulators. As highlighted within this paper, there are a number of challenges currently faced by researchers in achieving this goal. One of the key limiting agents is manipulator dexterity, which at present is inferior to that of the human hand. In order to overcome this, technological advancements are required in areas such as perception, sensing, planning and control.

Another key area which needs to be addressed is the development and integration of real-time processing into a manipulator's control strategy. This will provide the platform to allow robotic manipulators to detect and react to its surrounding environment, which is crucial for successful human-robot interaction. By developing this to a standard which ensures human safety, robotic manipulators can become an important enabler in assistive robotics and next generation systems.

7. REFERENCES

[1] H. I. Christensen, K. Goldberg, V. Kumar, and E. Messina, "A Roadmap for U.S. Robotics: From Internet to Robotics," pp. 1 – 25, 2013.

[2] P. Mickle, "1961: A peep into the automated future." [Online]. Available: http://www.capitalcentury.com/1961.html. [Accessed: 24-Feb-2013].

[3] (Shadow Robot Company), "Shadow Dexterous Hand C6P6 Technical Specification," 2010.

[4] H. Kawasaki, T. Komatsu, K. Uchiyama, and T. Kurimoto, "Dexterous anthropomorphic robot hand with distributed tactile sensor: Gifu hand II," *Mechatronics, IEEE/ASME …*, pp. 782–787, 1999.

[5] J. Ueda and Y. Ishida, "Development of the NAIST-Hand with vision-based tactile fingertip sensor," *… and Automation, 2005. …*, no. April, pp. 2332–2337, 2005.

[6] R. Walker, "Shadow Dextrous Hand Model C6ME Prices," vol. 44, no. 3308007. pp. 1–5, 2011.

[7] M. Grebenstein and A. Albu-Schaffer, "The dlr hand arm system," *... (ICRA), 2011 IEEE …*, pp. 3175–3182, 2011.

[8] M. Diftler and J. Mehling, “Robonaut 2-the first humanoid robot in space,” *... (ICRA), 2011 IEEE ...*, vol. 1, pp. 2178–2183, 2011.

[9] A. Deshpande, Z. Xu, M. Weghe, and B. Brown, “Mechanisms of the Anatomically Correct Testbed Hand,” *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 1, pp. 238–250, 2011.

[10] T. Senoo and Y. Yamakawa, “Skillful manipulation based on high-speed sensory-motor fusion,” *... , 2009. ICRA’09. ...*, pp. 1611–1612, 2009.

[11] Hosmer Dorrance Corporation, “Body-powered prosthetic hand,” 2009. [Online]. Available: http://www.hosmer.com/products/hooks/index.html.

[12] M. Burke, “Wounded servicemember helps researchers test groundbreaking upper limb prosthesis,” *Stars and Stripes*, 2012. [Online]. Available: http://www.stripes.com/news/wounded-servicemember-helps-researchers-test-groundbreaking-upper-limb-prosthesis-1.176589#. [Accessed: 21-Jan-2013].

[13] C. Connolly, “Prosthetic hands from Touch Bionics,” *Industrial Robot: An International Journal*, vol. 35, no. 4, pp. 290 – 293, 2008.

[14] Bebionic, “Bebionic hand,” 2011. [Online]. Available: http://www.bebionic.com/.

[15] E. Sofge, “The Future History of Bionic Tech,” *Popular Mechanics*, 2012. [Online].Available: http://www.popularmechanics.com/science/health/prosthetics/the-future-history-of-bionic-tech-5#slide-4. [Accessed: 21-Jan-2013].

[16] H. Liu, “Exploring human hand capabilities into embedded multifingered object manipulation,” *Industrial Informatics, IEEE Transactions on*, vol. 7, no. 3, pp. 389–398, 2011.

[17] C. Yu, M. Jin, and H. Liu, “An analytical solution for inverse kinematic of 7-DOF redundant manipulators with offset-wrist,” *2012 IEEE International Conference on Mechatronics and Automation*, pp. 92–97, Aug. 2012.

[18] A. Hermann, Z. Xue, S. W. Ruhl, and R. Dillmann, “Hardware and software architecture of a bimanual mobile manipulator for industrial application,” *2011 IEEE International Conference on Robotics and Biomimetics*, pp. 2282–2288, Dec. 2011.

[19] J. Alcazar and L. Barajas, “Dexterous robotic hand grasping method for automotive parts,” *Humanoid Robots (Humanoids), 2010 ...*, pp. 282–287, 2010.

[20] J. Z. Zheng, S. De La Rosa, and A. M. Dollar, “An investigation of grasp type and frequency in daily household and machine shop tasks,” *2011 IEEE International Conference on Robotics and Automation*, pp. 4169–4175, May 2011.

[21] B. Cohen, S. Chitta, and M. Likhachev, “Search-based planning for dual-arm manipulation with upright orientation constraints,” *2012 IEEE International Conference on Robotics and Automation*, pp. 3784–3790, May 2012.

[22] B. Bauml and F. Schmidt, "Catching flying balls and preparing coffee: Humanoid rollin'justin performs dynamic and sensitive tasks," ... *(ICRA), 2011 IEEE ...*, pp. 3443–3444, 2011.

[23] L. Chang, J. Smith, and D. Fox, "Interactive singulation of objects from a pile," *Robotics and Automation (ICRA), ...*, no. Section IV, pp. 3875–3882, 2012.

[24] S. Patil, J. van den Berg, and R. Alterovitz, "Motion planning under uncertainty in highly deformable environments," *Robotics: Science and ...*, pp. 241–248, 2012.

[25] Y. Bekiroglu and J. Laaksonen, "Assessing grasp stability based on learning and haptic data," *Robotics, IEEE ...*, vol. 27, no. 3, pp. 616–629, 2011.

[26] B. Struijk, "A new understanding of modern robotics," pp. 248–259, 2012.

[27] C. Park, J. Kyung, and D. Park, "Development of an industrial robot manipulator for the easy and safe human-robot cooperation," *Control Automation and Systems (...*, pp. 678–681, 2010.

[28] E. a. Sisbot and R. Alami, "A Human-Aware Manipulation Planner," *IEEE Transactions on Robotics*, vol. 28, no. 5, pp. 1045–1057, Oct. 2012.

[29] A. Dietrich and T. Wimbock, "Extensions to reactive self-collision avoidance for torque and position controlled humanoids," ... *(ICRA), 2011 IEEE ...*, pp. 3455–3462, 2011.

[30] N. Najmaei and M. R. Kermani, "Prediction-based reactive control strategy for human-robot interactions," *2010 IEEE International Conference on Robotics and Automation*, pp. 3434–3439, May 2010.

[31] F. Zacharias, C. Schlette, F. Schmidt, C. Borst, J. Rossmann, and G. Hirzinger, "Making planned paths look more human-like in humanoid robot manipulation planning," *2011 IEEE International Conference on Robotics and Automation*, pp. 1192–1198, May 2011.

[32] J. Aleotti, V. Micelli, and S. Caselli, "Comfortable robot to human object hand-over," *2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication*, pp. 771–776, Sep. 2012.

[33] T. Deyle, "Electroadhesive Robot Grippers from SRI International," 2010. [Online].Available: http://www.hizook.com/blog/2010/10/28/electroadhesive-robot-grippers-sri-international.