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Dexterous Gripper for In-Hand Manipulation with Embedded Object Localization Algorithm

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Abstract

Since the last decade, thanks to the spreading of the concept of Industry 4.0 and Smart Factory, more and more companies have started to investigate the robotic field looking for reliable solutions aiming at improving the efficiency of assembly lines. Promising technologies are connected to the speeding up of production stages like fast algorithms for object localization, as well as dexterous grippers for manipulation and assembly. Nowadays, most of the solutions for pick and place tasks involve the use of robotic grippers for grasping objects, while robotic manipulators are responsible for their accurate placements. Focusing on the grippers, although their simple structure can be appreciated, it greatly reduces their in-hand manipulation abilities, making unfeasible the twists of grasped objects and their release in a desired pose. As consequence, the efficiency of the pick and place operation is reduced since several adjustments of the robotic arm are required to accomplish the task.
In this paper, a novel dexterous gripper coupled with a vision system algorithm for object localization and pose estimation are presented, and their performances in manipulating different objects are discussed. The designed gripper has a symmetrical structure with two finger modules, each one consisting in a couple of linear actuators arranged mutually orthogonal, so the translations in two axis, namely y and z directions, are allowed. As terminal part of each finger there is a revolute joint to whom is attached a fingertip modelled according to the shape of the target objects and easily replaceable. The embedded vision system algorithm adopted estimates position and orientation of the objects on a flat surface, and it coordinates the gripper placement to grasp them. The case study of the handling of a Spanish fan is presented and discussed in details.

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1. Main text

Nowadays, every productive sector borrows from the robotic research all the reliable technologies to reduce production costs, improve quality checks and speed up the production itself. In fact, robotic devices have proven their superiority over humans in a few of crucial aspects connected to the production. In pick and place tasks, for example, it is well known that a robotic system far exceeds human work force in terms of handling heavy weights, positioning them with accuracy and ensuring high repeatability of placements.

Despite all these advantages, there are still specific skills in which humans remain unbeaten and the technology has a long way to go to match these abilities. Two of these sectors are the dexterous in-hand manipulation and the flexibility in adapting to unexpected changes. The former is the skill of releasing objects in a desired configuration independently from their initial pose, the latter is the ability of perceiving their orientations and eventually re-planning the grasp accordingly.

Many researchers have addressed these problems over the years, looking for a common definition of dexterity in robotics [1], formalizing it from the theoretical point of view [2], and suggesting possible paths to explore toward simple solutions to the problem [3].

The robotic devices developed until now are many and can be categorized in two main families according to their features: bio-inspired hands and industrial grippers.

In the former category, there are robotic devices that, taking inspiration from the nature, try to mimic the human hand features and its behavior [4], [5], [6]. The DLR hand [7], or the PISA/IIT softHand [8], for example, are underactuated hands driven by a tendons system. They can grasp soft objects and can comply to fit many shapes. However, accuracy and speed are hardly achieved due to their designs. The BarrettHand [9] is somehow in the middle between bio-inspired hand and industrial gripper, with three underactuated fingers, it can accomplish a large number of grasps, but it lacks in dexterity and in-hand manipulation abilities.

Reviews on industrial grippers are presented in [10], [11], [12], where the most common designs are described. In general, industrial grippers appear to be very specialized tools, their simple structure lacks in dexterity limiting their potential. Additional devices to enhance their mobility are sold separately. Thus, in the last decades, the researchers have oriented on studying designs more flexible, and develop advanced tools for filling this gap. In [13] the authors propose a two-fingered gripper with active surface that aim at manipulating the objects controlling the adhesion of fingers and the tracks slide. The dexterous gripper, described in [14], allows fast rotation of cylindrical objects along their main rotation axis and is flexible enough to grasp a variety of payloads. The grippers presented in [15] and [16] have interesting features, since with four modular fingers they prove their dexterity in rotating spherical objects around the main axis by breaking and re-creating alternatively the contacts. However, its dexterity comes to the price of high number of actuators, thus the control complexity increases as well as the chances of mechanical failure.

In this work, we propose a new dexterous gripper that has two modular fingers for grasping objects and two revolute joint as fingertip for changing their orientation. Its design has been developed for manipulating a Spanish fan for competing in the IROS 2018 Fan Robotic Challenge [17]. The resulting gripper allows fast and independent rotations around the fingertip axis opening and closing the Spanish fan in few seconds. It is worth to underline that with a slightly change in fingertip paddles it is possible to extend the range of application of the device. In fact, it proofs well in handling a good variety of objects twisting and releasing them in the desired pose.

In the next section, the experimental setup is described, the gripper kinematics and the dexterous manipulation problem are discussed and solved. In section 3, the experimental results are reported. Conclusion and future works are assessed in section 4.

2. System Design

The overall system, shown in Fig. 1(a), consists in the vision system, the robotic arm and the gripper. The vision system is on top of the cabinet, close to the arm base in order to maximize its vision field. The camera points straight to the flat plane below, where the Spanish fan is. The robotic arm Universal Robot UR3 [18] is fixed upside down on the cabinet, in this way its admissible workspace is almost all the cabinet plane. The UR3 places the gripper over the coordinates provided by the pose estimation algorithm. Once the grasp is secured, the arm lifts its payload to a safe position avoiding any possible collision during the handling phase.

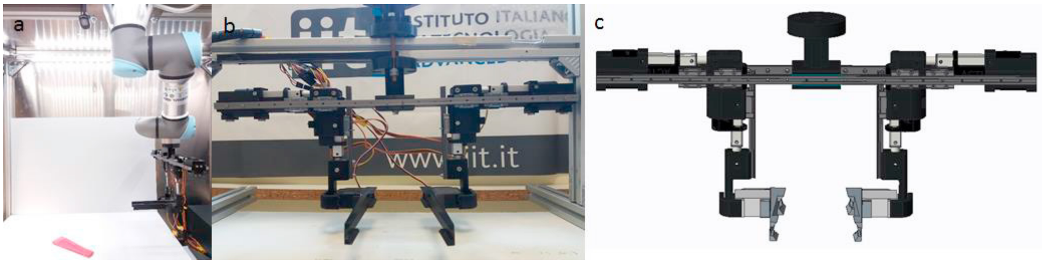

Fig. 1. (a) Experimental setup: the pink Spanish fan lays on the table, the camera and the Universal Robot UR3 are attached on top, and the gripper is the end effector. (b) Gripper prototype built with 3D printing, (c) CAD model of the gripper.

The gripper, shown in Fig. 1(b)-(c), is designed with a modular structure so it is easy to add or remove other fingers to adapt it to new tasks. The linear guides constitute the main structure of the system, they ensure the correct sliding of the fingers as well as they correct misalignments in prototype assembling.

Each finger module has two degrees of freedom (DOFs) driven independently by two linear actuators. One prismatic joint is aligned according to x axes of the world frame and moves along the guides driving the second which slides orthogonally along the z axis.

At each fingertip there is a revolute joint to whom is attached a paddle. As shown in Fig. 1(b)-(c), the corners of the paddle form a concave shell that is shaped as the Spanish fan lateral profile. As a matter of fact, this geometry is meant to force, during grasping, the Spanish fan external layers in the shell securing as well a correct alignment between the fan pivot and the revolute joint axis.

The two finger modules are symmetric w.r.t. the vertical $y - z$ plane and they grant a good in-hand manipulation dexterity as proven in the next subsection.

2.1. Gripper kinematics

Grasping an object is a high precision demanding task to tackle. Many strategies are possible, in this work the problem is solved controlling the Cartesian position of each gripper finger. To do so, the gripper is modeled initially as a two serial kinematic chains, as shown in Fig. 2(a). Following the rules of the Denavit-Hartenberg convention, the fixed frame $\{W\}$, in black, is chosen in the middle of the gripper base, while local frames $\{O_i\}$ in red, are placed in correspondence of each joint.

The Jacobian matrix $\mathbf{J}_\mathrm{r} \in \mathbb{R}^{6x3}$ of the right finger maps the joint velocity vector $\dot{\mathbf{q}}_\mathrm{r} = [\dot{\mathbf{d}}_{1\mathrm{r}} \quad \dot{\mathbf{d}}_{2\mathrm{r}} \quad \dot{\mathbf{q}}_{3\mathrm{r}}]^\mathrm{T}$ into the Cartesian twist $\boldsymbol{\xi}_\mathrm{r} \in \mathbb{R}^{6x1}$, and it is:

$$J_r = [J_{1r}|J_{2r}|J_{3r}] = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (1)$$

The Jacobian matrix $\mathbf{J}_l \in \mathbb{R}^{6x3}$ of the left finger is:

$$J_l = [J_{1l}|J_{2l}|J_{3l}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (2)$$

It is clear that each finger can slide along x, z directions, and can rotate around the x axis w.r.t. $\{W\}$, so the proposed gripper design can accomplish the handling of the Spanish fan.

Once grasped, the object can be moved into new positions or twisted configurations imposing the corresponding joint velocities. To compute them it is necessary to solve the dexterous manipulation problem [2].

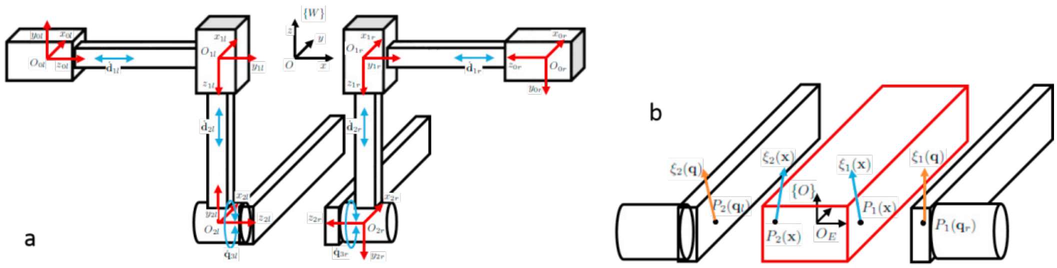

Fig. 2. (a) Gripper kinematic model: the world frame $\{W\}$ (in black), the local frames $\{O_i\}$ (in red), the joint velocities (in blue). (b) Dexterous manipulation problem: the twist $\boldsymbol{\xi}_i(\mathbf{x})$ of point P_i due to the twist $\boldsymbol{\xi}_E$ of the frame $\{O_E\}$ (in blue), the twist $\boldsymbol{\xi}_i(\mathbf{q})$ of point P_i due to joint variables (in orange).

The origin of coordinate frame $\{O_E\}$ is placed in the middle of the Spanish fan pivot, as shown in Fig. 2(b), and its velocity vector is named $\boldsymbol{\xi}_E \in \mathbb{R}^{6x1}$, the twist $\boldsymbol{\xi}_i \in \mathbb{R}^{6x1}$ on the i-th contact point results:

$$\xi_i(x) = B_i \xi_E = \begin{bmatrix} I_{3x3} & -\widehat{O_E P_i} \\ 0_{3x3} & I_{3x3} \end{bmatrix} \xi_E \quad (3)$$

Where $\mathbf{B}_i$ is known as the *grasp Jacobian* of the i-th contact point, $-\widehat{O_E P_i}$ is the skew symmetric matrix of the vector $O_E P_i = [a_i \quad 0 \quad 0]^T$, which is the position vector of the point P_i w.r.t. the frame $\{O_E\}$. With a compact notation, it is possible to write:

$$\boldsymbol{\xi}(\boldsymbol{x}) = \begin{bmatrix} \boldsymbol{\xi}_1(\boldsymbol{x}) \\ \boldsymbol{\xi}_2(\boldsymbol{x}) \end{bmatrix} = \begin{bmatrix} \boldsymbol{B}_1 \\ \boldsymbol{B}_2 \end{bmatrix} \boldsymbol{\xi}_E \tag{4}$$

All the twists of the contacts depend also on joint variables:

$$\boldsymbol{\xi}(\boldsymbol{q}) = \begin{bmatrix} \boldsymbol{\xi}_1(\boldsymbol{q}) \\ \boldsymbol{\xi}_2(\boldsymbol{q}) \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_r & \boldsymbol{0}_{6x3} \\ \boldsymbol{0}_{6x3} & \boldsymbol{J}_l \end{bmatrix} \dot{\boldsymbol{q}} = \boldsymbol{J}\dot{\boldsymbol{q}} \tag{5}$$

Where $\mathbf{J}_r$ and $\mathbf{J}_l$ are the right and left finger Jacobian matrix respectively. $\mathbf{J}$ is known as *hand Jacobian*, and the vector $\dot{\mathbf{q}} = [\dot{\mathbf{q}}_r \quad \dot{\boldsymbol{q}}_l]^T$ includes the joint velocity vectors of both fingers.

Now, let $\mathbf{H}_i$ define the contact type matrix, which represents the contact constraints between the i-th finger and the corresponding point on the object, it is modeled as:

$$\boldsymbol{H}_i = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{6}$$

The first three rows of the matrix constrain the relative sliding along the axis, the last row prevent the relative rotation between object and finger, around the x axis. The complete matrix of contacts for both finger is then:

$$\boldsymbol{H} = \begin{bmatrix} \boldsymbol{H}_1 & \boldsymbol{0}_{4x6} \\ \boldsymbol{0}_{4x6} & \boldsymbol{H}_2 \end{bmatrix} \tag{7}$$

Solving the dexterous manipulation problem means finding all the possible joint velocities $\dot{\mathbf{q}}$ and the object twists $\boldsymbol{\xi}_E$ that satisfy:

$$[\boldsymbol{HJ}|-\boldsymbol{HB}] \begin{bmatrix} \dot{\boldsymbol{q}} \\ \boldsymbol{\xi}_E \end{bmatrix} = \boldsymbol{0} \tag{8}$$

The kernel computation of the matrix $[\mathbf{HJ}|-\mathbf{HB}]$ provides the solution to the problem:

$$ker[\boldsymbol{HJ}|-\boldsymbol{HB}] = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & a \\ 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & -a \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (9)$$

Analyzing the matrix in eq. 9 column by column, it is clear that, the grasped object can be translated along the x and z directions; paddle coordinate rotations result in twisting the Spanish fan around its x axis; moreover, imposing opposite velocities to the vertical prismatic joints, the grasped object rotates around its y axis. This theoretical degree of freedom, however, has not been validated yet experimentally, anyway the assumption that small relative rotations between fingers and object may occur is conceivable.

2.2. Vision system and pose estimation algorithm

As described at the beginning of this section, the vision system consists in a fixed camera, Logitech Webcam C170 [19], which is placed at the top of the cabinet. The goal of the pose estimation algorithm is to retrieve the middle point P_h on the Spanish fan pivot and the object orientation θ on the plane w.r.t. the camera frame. Once the Spanish fan is within the workspace, the camera takes a picture of the environment and the pose estimation algorithm starts. Through standard image process, the photo is converted in greyscale, and the Shi-Tomasi corner detector algorithm [20] is tuned to identify the four corners on the perimeter of the Spanish fan.

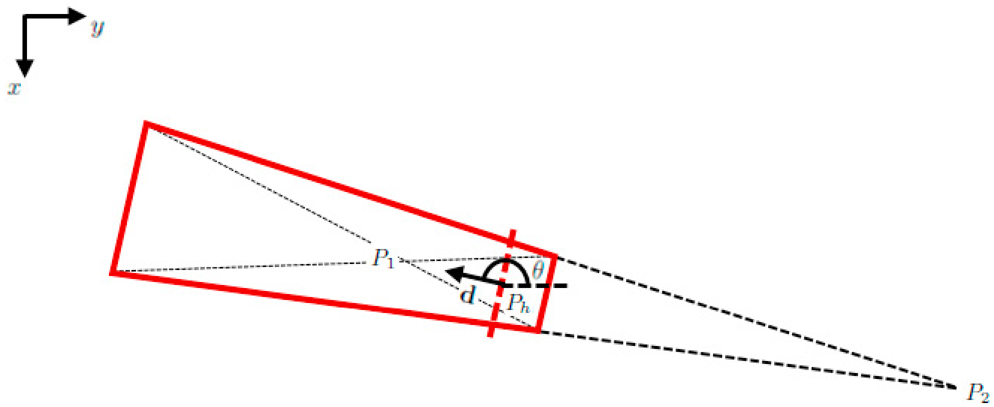

Fig. 3. Schematization of the pose estimation problem. On the Spanish fan (in red) are shown the main variables involved in the problem and the camera frame (in black).

The pose estimation is based on two assumptions: the Spanish fan has a trapezoidal shape, and it lies on one of its larger surfaces. The algorithm computes the point P_1 as the intersection of the object diagonal lines, as well as the point P_2 as the intersection of the Spanish fan longest edges.

The unitary vector $\mathbf{d} = P_1 - P_2 \,/\, \|P_1 - P_2\|$ defines the direction of the object bisecting line from which is possible to retrieve the body orientation θ w.r.t the camera frame. Finally, the pivot central position is computed as $P_h =$

$P_1 - l\mathbf{d}$, where l is the measure of the distance between P_1 and the central point P_h on the Spanish fan pivot and it is known by the geometry of the object.

3. Results

Many experiments have been done in order to verify the gripper performance and validate the algorithm. The main manipulation phases are illustrated in Fig. 4.

The Spanish fan is placed randomly within the workspace; the algorithm computes the pose estimation and send that information to the UR3. The arm moves toward the target, aligning the gripper to the estimated orientation while maintaining a small vertical offset to prevent any collisions.

The gripper fingers fill this vertical gap while grasping, Fig. 4(b). During this phase, the paddle shape forces the match of the center of rotations of both the gripper and the fan by lifting the latter until it reaches its shell.

Once the grasp is secured, the arm moves up and the gripper starts the handling phase. According to the results of eq. (9), rotating the right finger by 90° and the left one by -90°, the Spanish fan aligns along the vertical. From this point, a further rotation of 90° for both fingers results in the complete opening of the Spanish fan, Fig. 4(c). At the end, the gripper closes the fan and releases it on the table, Fig 4(d).

The entire operation is timed: the grasp, the handling and the release phases take 8-9*s*; the entire operation takes 21*s*.

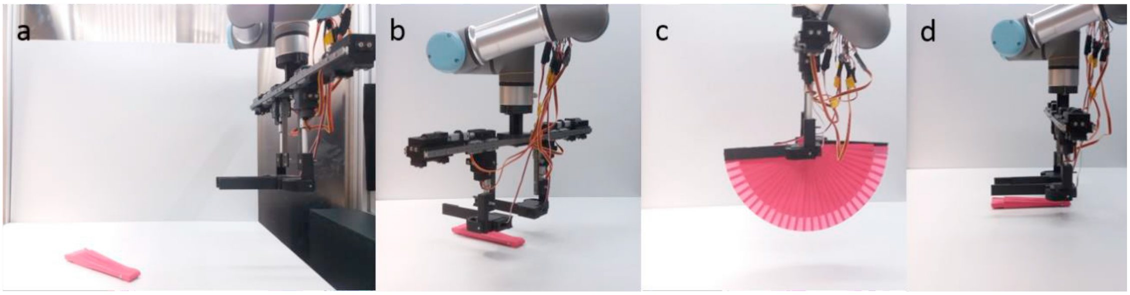

Fig. 4. Sequences of Spanish fan handling. (a) The Spanish fan is within the workspace in random pose. (b) The algorithm estimates the object pose and sends it to the UR3 arm, which moves toward those coordinates. (c) The gripper grasps the Spanish fan and handles it applying the velocities calculated in eq. 9. (d) The gripper releases the Spanish fan on the table before being moved to the starting position again.

4. Conclusions

In this paper, a new modular gripper design for assessing the manipulation of a Spanish fan is proposed, analyzed and tested. The gripper kinematics has been described and the device dexterity in handling objects has been proved. The solutions to the dexterous manipulation problem are discussed; since they map joint velocities into twists of the object, they result crucial in determine the control actions for producing the desired manipulation of the grasped object.

The pose estimation algorithm has been experimentally validated as well. Finally, experimental results are reported and discussed.

Future work will focus on extending the results obtained in this very peculiar case. In particular, a more efficient kinematic chain will be investigated to improve the dexterity of the gripper keeping the total number of driving actuators limited. Moreover, a general-purpose fingertip design will be addressed to widening the field on application of the system. Finally, improvements on the pose estimation algorithm will expect to include a shape classification, making the system more flexible and robust w.r.t geometry changes in objects.

References

[1] R. R. Ma and A. M. Dollar, "On dexterity and dexterous manipulation", *15th International Conference on Advanced Robotics (ICAR)*, Tallin, 2011, pp. 1-7.

[2] A. M. Okamura, N. Smaby and M. R. Cutkosky, "An overview of dexterous manipulation", *Proceedings 2000 ICRA. Millennium Conference, IEEE International Conference on Robotics and Automation*. Symposia Proceedings (Cat. No.00CH37065), San Francisco, CA, USA, 2000, vol.1, pp. 255-262.

[3] A. Bicchi, "Hands for dexterous manipulation and robust grasping: a difficult road toward simplicity", in *IEEE Transactions on Robotics and Automation*, Dec. 2000, vol. 16, no. 6, pp. 652-662.

[4] E. Mattar, "A survey of bio-inspired robotics hands implementation: New directions in dexterous manipulation", *Robotics and Autonomous Systems*, May, 2013, v. 61, n. 5, pp. 517-544.

[5] J. T. Belter, J. L. Segil, A. M. Dollar, and R.F. Weir, "Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review", *Journal of Rehabilitation Research and Development*, 2013, vol. 50, no. 5, pp. 599–618.

[6] J. W. Martell and G. Gini, "Robotic hands: Design review and proposal of new design process", in *World Academy of Science, Egineering and Technology,* 2007, vol. 26, pp. 85-90.

[7] M. Grebenstein et al., "The DLR hand arm system", *2011 IEEE International Conference on Robotics and Automation*, Shanghai, 2011, pp. 3175-3182.

[8] M. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, A. Bicchi, "Adaptive synergies for the design of the Pisa/IIT SoftHand", *The International journal of Robotics Research*, 2014, vol. 33, pp. 768-782.

[9] W. Townsend, "The BarrettHand grasper – programmably flexible part handling and assembly", *Industrial Robot: An International Journal*, 2000, vol. 27, pp. 181-188.

[10] R. V. Bostelman, J. A. Falco, "Survey of industrial manipulation technologies for autonomous assembly applications", *NISTIR 7844, Intelligent Systems Division, National Institute of Standards and Technology*, Gaithersburg, USA, 2012.

[11] S. Raval, B. Patel, "A review on Grasping Principle and Robotic Grippers", *International Journal of Engineering Development and Research,* vol. 4. 2016. pp. 483-490.

[12] N. V. Sabnis, "A Review: State of The Art of Robotic Grippers", *International Journal of Engineering and Technology*, 2018.

[13] V. Tincani et al., Velvet fingers: "A dexterous gripper with active surfaces", *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vilamoura, 2012, pp. 1257-1263.

[14] F. Chen, F. Cannella, C. Canali, T. Hauptman, G. Sofia and D. Caldwell, "In-hand precise twisting and positioning by a novel dexterous robotic gripper for industrial high-speed assembly", *IEEE International Conference on Robotics and Automation (ICRA)*, Hong Kong, 2014, pp. 270-275.

[15] N. Rahman, M. D'Imperio, L. Carbonari, M. Palpacelli, F. Cannella and D. Caldwell, "Kinematic analysis and synthesis of a novel gripper for dexterous applications", *12th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA)*, Auckland, 2016, pp. 1-6.

[16] N. Rahman, D. Caldwell, F. Cannella, "VARO-Fi: A Variable Orientable Gripper to Obtain In-Hand Manipulation", 2018, pp. 4568-4575.

[17] IROS 2018 Fan Robotic Challenge, [Online], Available: https://www.iros2018.org/fan-robotic-challenge [Accessed 04 02 2019].

[18] Universal Robots, "UR", [Online], Available: https://www.universal-robots.com/products/ur3-robot7 [Accessed 04 02 2019].

[19] Logitech Webcam C170, [Online], Available: https://support.logitech.com/en_us/product/webcam-c170/specs [Accessed 04 02 2019].

[20] J. Shi and Tomasi, "Good features to track", *Proceedings of IEEE Conference on Computer Vision and Pattern Recognition*, Seattle, WA, USA, 1994, pp. 593-600.