Analytical approach to reorient unknown objects via in-hand manipulation

Morad Shirzadi
Inst. of Industrial and Control Eng.
Universitat Politècnica de Catalunya
Barcelona, Spain
morad.shirzadi.maryan@upc.edu

Isiah Zaplana
Inst. of Industrial and Control Eng.
Universitat Politècnica de Catalunya
Barcelona, Spain
isiah.zaplana@upc.edu

Raúl Suárez
Inst. of Industrial and Control Eng.
Universitat Politècnica de Catalunya
Barcelona, Spain
raul.suarez@upc.edu

***Abstract*—This paper introduces a novel strategy to enhance the dexterous in-hand manipulation capabilities of robotic hands, focusing on reorienting unknown objects around any specified axis. The proposed method leverages tactile sensing and sensor-to-motor mapping to achieve precise and adaptive manipulation without prior object knowledge. The strategy employs circular finger movements to maintain stable and secure grasps, ensuring even pressure distribution. Preliminary experiments conducted with the Allegro robotic hand validate the efficacy of the approach across various orientations, demonstrating its potential for practical applications.**

***Index Terms*—in-hand manipulation, reorienting unknown objects, tactile sensing**

I. Introduction

In recent years, the ability of robotic hands with multiple fingers to reorient grasped objects has attracted substantial interest in robotics, emerging as an important area of research. This field is mainly divided into two key areas. First, the design and manufacturing of dexterous robotic hands capable of complex motions and interactions with objects; and second, the creation of algorithms and strategies that enable the robotic hands to determine the optimal way of picking up and handling various types of objects. Furthermore, the development of reliable tactile sensing devices and control algorithms has enhanced the dexterity of robotic hands [1].

However, robust and reliable manipulation of unknown objects remains an open challenge in robotics due to the high dimensional actuation space associated with multi-fingered robotic hands, and the frequent change in the contact state between fingers and objects. The uncertainty around these attributes leads to unpredictable interactions and failures during grasping and manipulation. This capability gap highlights the need for advancements in the adaptive manipulation of unknown objects [2].

Robotic grippers span a wide spectrum, ranging from simple grippers to highly complex anthropomorphic designs. While simple grippers offer strength and simplicity, they lack the ability to manipulate objects dexterously. In contrast, multi-fingered robotic hands provide greater flexibility for in-hand object reorientation and positioning [3]. In particular, many robotic hands were designed to replicate the physical structure and capabilities of the human hand [4]. However, the complexity of such mechanics introduces multiple challenges for their correct programming and control, especially in dexterous in-hand manipulation [5].

In-hand manipulation refers to the ability of a robotic hand to dexterously manipulate objects, performing precise movements to change the object's position and orientation relative to the hand. In addition, tactile sensors enable robotic hands to manipulate objects using real-time sensory input, rather than relying on the object model. This allows the robot to grasp and manipulate items successfully even without prior knowledge of their exact shape and size [1], [6]. Tactile feedback is vital in applications that consider interactions between the manipulated object and its environment [7].

In-hand manipulation strategies with a dexterous and anthropomorphic robotic hand are commonly split into three different categories [8]: (1) rolling motion, (2) sliding motion, and (3) finger relocation . These modes can be combined to perform more sophisticated manipulative procedures. Rolling motion [9] focuses on rolling the fingers over the object to reposition it, while sliding motion occurs when the tangential force exceeds the normal force multiplied by the friction coefficient between the object and the fingertip [10]. Finally, finger relocation, allows fingers to temporarily release contact with the object and re-establish it at a different location, thereby changing the grasp configuration [11].

Most related works in robotic in-hand manipulation focus on object reorientation, typically overlooking tactile feedback in the manipulation process. For example, a model-free reinforcement learning policy was proposed to reorient a large number of objects across different scenarios, however, these experiments were confined to simulations [12]. Regarding sensory input, another approach involving a parallel jaw finger gripper only relies on visual feedback, not tactile sensing [13]. This lack of tactile sensory feedback restricts the practical applicability of such methods. Additionally, these vision-based experiments demand substantial Graphics Processing Unit (GPU) memory. In contrast, this paper introduces an analytical approach to achieve similar results, thereby simplifying the procedure and facilitating an easy implementation across various software platforms and robotic hands.

This work was partially supported by the Project PID2020-114819GB-I00 funded by MICIU/AEI/10.13039/501100011033".

In particular, this paper aims to enhance robotic in-hand manipulation by focusing on the reorientation of unknown objects around any desired axis. The proposed approach does not presuppose prior knowledge of the objects; instead, utilizes tactile sensing to compute the proper finger movements. This method is applicable to any fully-actuated anthropomorphic hand.

II. Methodology

This paper introduces an innovative strategy designed to rotate objects around any specified axis. To do this, a specific rotation around a predetermined axis, represented by its direction vector u, and a point in space c, is defined. The goal is to reorient the object to a desired rotation angle γ relative to the initial grasped configuration, with a step size θ for each iteration. The strategy leverages feedback from tactile sensors and the configuration of the robot's hand, ensuring that the object remains securely grasped throughout the manipulation process.

To achieve this, the proposed strategy uses circular movements of the fingertips around the rotation axes to produce the object reorientation while ensuring even pressure distribution. Figure 1 illustrates the paths of two fingers when an object rotates around the three main axes of a given reference frame, namely x, y, and z.

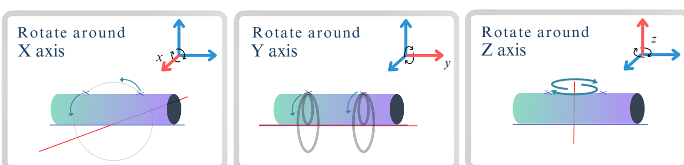


Fig. 1: Schematic representation of the circular paths followed by two fingertips when rotating an object around: (a) the x axis, (b) the y axis and (c) the z axis.

Employing finger circular paths for in-hand manipulation splits the problem into several stages. First, several frames must be determined. Following this, the contact forces exerted by each finger need to be adjusted based on real-time sensory feedback, allowing for dynamic control of grip strength to maintain a stable contact. Then, points in space are selected to outline the circular movement path, plotting a precise trajectory for each fingertip around the chosen axis and facilitating smooth and controlled object rotation. Finally, the values for the joint variables of each finger to reach these points are computed, and the hand is moved to the resulting configuration.

A. Assumptions and frames definition for object's reorientation

It is assumed that the object has already been securely grasped using n fingers. Four distinct frames are required for each finger (see Figure 2):

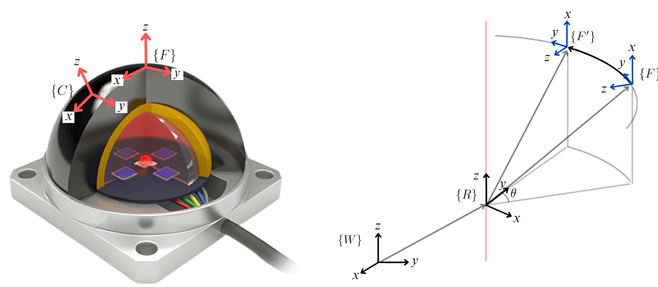
1) Contact frame $\{C\}$: This frame has the origin at the contact point p between the finger and the object. The y-axis is aligned parallel to the axis of the finger's last joint. The z-axis is oriented perpendicular to the the sensor's surface at the contact point. The x-axis is derived from the cross product between the y and z axes.

2) Fingertip frame $\{F\}$: Located at a specific fingertip point p_f on the surface of the sensor. The y-axis is aligned parallel to the finger's last joint axis. The z-axis is oriented perpendicular to the surface of the sensor at the fingertip point p_f, which depends on the sensor used. Finally, x-axis is generated from the cross product of the y and z axes.

3) Rotation axis frame $\{R\}$: The origin of this frame lies at a point c defined by the user. The z-axis is aligned with the rotation axis, while any two orthogonal vectors, v_1 and v_2, are considered as basis vectors serving as the x-axis and the y-axis, respectively.

4) World reference frame $\{W\}$: It is located on the palm of the hand, and serves as the global reference frame.

To relate all these frames, homogeneous transformation matrices are used. In particular, let T_{wf} be the transformation matrix that describes the fingertip frame $\{F\}$ relative to the world reference frame $\{W\}$, and T_{wr} be the transformation matrix to express the rotation axis frame $\{R\}$ relative to the world reference frame $\{W\}$.



(a) (b)

Fig. 2: (a) Contact and fingertip frames on the surface of the fingertip sensor; (b) Relation of the current and updated fingertip frames, $\{F\}$ and $\{F'\}$, with the rotation axis and world frames, $\{R\}$ and $\{W\}$.

B. Force adjustment

During the manipulation process, it is essential to monitor and adjust the forces applied by the fingertips in each step. At each iteration of the manipulation strategy, for each finger, the force error, e, is computed as the difference between the actual force, f, detected by the tactile sensors, and the desired force, f_d:

$$e = f - f_d$$

To adjust the grasping force, the fingertip point p_f is moved along the z-axis of the contact frame $\{C\}$. The adjustment magnitude, δ, is calculated based on the force error e as:

$$\delta = \begin{cases} f_1(e) & \text{if } e \leq 0 \\ f_2(e) & \text{if } e > 0 \end{cases}$$

where $f_1(e)$ and $f_2(e)$ are predefined functions designed to make the applied force to quickly converge to the desired force. Since the main idea is to move the fingertip frame $\{F\}$ along a circular path to reorient the object, the force adjustment is applied to the fingertip point p_f but in the z direction of the contact frame, where the current force f is applied and sensed by the tactile sensors. Therefore, p_f is adjusted in the z-direction of the contact frame $\{C\}$. The updated fingertip position p_f^* is calculated as:

$$p_f^* = p_f + \delta z_c$$

Subsequently, the transformation matrix T_{wf} is updated to reflect the new position p_f^*:

$$T_{wf} = \begin{bmatrix} R_{wf} & p_f^* \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} R_{wf} & p_f + \delta z_c \\ 0 & 1 \end{bmatrix}$$

In this matrix, R_{wf} remains the same as the orientation of the fingertip frame relative to the world frame is unchanged, while the position p_f^* is updated to reflect the force adjustment.

This update ensures that the grasping force is dynamically regulated in response to real-time sensory feedback, thereby enhancing the reliability and precision of the manipulation process.

C. Trajectory planning

In order to achieve the desired reorientation, the transformations that dictate the movement of the fingertips must be computed. For this, the relationship between the frame attached to each fingertip and the rotation axis is considered.

Given the known transformations T_{wf} and T_{wr}, T_{rf} can be computed as:

$$T_{rf} = T_{wr}^{-1} \cdot T_{wf}$$

To manipulate the object, the adjusted fingertip frame needs to be rotated by an angle θ around the z-axis of $\{R\}$, z_r. This rotation is represented as:

$$T_{rf'} = T(z_r, \theta) \cdot T_{rf}$$

where

$$T(z_r, \theta) = \begin{bmatrix} & & & 0 \\ & R(z_r, \theta) & & 0 \\ & & & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

with $R(z_r, \theta)$ the rotation matrix defining the rotation around axis z_r by an angle θ, given by:

$$R(z_r, \theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Finally $T_{rf'}$ is the transformation matrix of the fingertip frame $\{F\}$ after rotation. The new fingertip frame, $\{F'\}$, can be expressed relative to the world frame $\{W\}$ as:

$$T_{wf'} = T_{wr} \cdot T_{rf'}$$

This process ensures that the fingertip moves along the desired path, achieving precise manipulation of the object. Figure 2 (b) depicts the reference frames before and after the rotation.

D. Moving the finger

To move the finger from frame $\{F\}$ to frame $\{F'\}$, two steps must be followed:

1) Step-1: Determining the configuration of the finger in the new position: The configuration of each finger, Q_i, is determined via inverse kinematics with $\{F'\}$ as the desired position and orientation. The inverse kinematics is computed in closed-form using Paul's method [14].

2) Step-2: Moving the fingers to the new configuration: If the values of the joint variables computed via the inverse kinematics are reachable, then the fingers are moved to the new configuration.

Algorithm 1 presents the pseudo code of the proposed strategy for manipulating and reorienting an unknown object around any desired axis.

Algorithm 1: Reorienting an unknown object

Input: p_i,f_d ,u ,c,θ,γ

```
k ← 0, a ← 0, stop ← false
for i = 1, ..., n do
while stop ≠ true or a ≤ number of steps = γ/θ do
    Compute δ_i(k) from e_i(k)
    Compute p*_fi(k) using p*_fi(k) = p_fi(k) + δz_ci
    Compute p_f'i based on manipulation strategy
    Compute Q_i(k+1) from {F'} via inverse kinematics
    if the new point is within the workspace then
        Move finger i to Q_i(k+1)
    else
        stop ← true
    k ← k + 1, a ← a + 1, f ← f'
```

III. Validation

In the experiments, the Allegro hand from Wonik Robotics was employed [15], featuring a four-finger anthropomorphic design with each finger having four degrees of freedom (DOF). The Index, Middle, and Ring fingers share a common kinematic structure, with the first DOF establishing the orientation of the finger working plane. The subsequent three DOFs, responsible for flexion and extension, enable the fingertip to reach specific points and orientations within this plane. Conversely, for the Thumb, the first DOF enables abduction movements, and the second DOF sets its working plane orientation, which restricts its capabilities to only two DOFs for manipulation within this plane, thus the position and orientation of the Thumb's fingertip cannot be independently controlled. The hand's joints are equipped with DC motor

Fig. 3: First row left: Allegro hand equipped with the Optoforce tactile sensors. First row right: the objects manipulated during the experiment. Second and third rows: Different sequences of the reorientation, in the x-axis of the reference frame, of the grasped object.

actuators and potentiometers that measure position with a resolution of 0.002 degrees. The hand interfaces with a PC through a CAN bus, and features PID position controllers for each joint with gravity compensation [16]. Additionally, OptoForce tactile sensors were utilized to provide real-time feedback on contact forces during manipulation.

To evaluate the efficacy of the proposed manipulation strategy, a series of tests have been conducted considering as rotation axis the main coordinate axes: x, y, and z of the world reference frame $\{W\}$, as illustrated in Figure 3. These axes were chosen to demonstrate the strategy's adaptability and robustness across a variety of orientations, essential for practical robotics applications where the desired object orientation can be highly variable.

In the experiments, the parameter γ representing the total desired angle of rotation for reorienting an object was set to 35, 15, and 50 degrees for rotations around the x, y, and z axes, respectively. The parameter θ denoting the size of each step in degrees, was set to 0.005.

The functions used for computing the adjustment magnitude δ based on the force error e are defined as follows:

$$\delta = \begin{cases} \lambda \, \|e\| & \text{if } e \leq 0 \\ -\lambda \, \|e\| & \text{if } e > 0 \end{cases}$$

where λ is a scaling factor that determines the magnitude of the adjustment, with a value of 0.001 m and a value for the desired contact force of 5N.

Videos demonstrating the preliminary results of the system performance for each scenario in the sets of experiments can be viewed at https://youtu.be/jEdVfAVMXF0.

IV. Conclusions

This paper presents a novel strategy for enhancing the dexterous in-hand manipulation capabilities of robotic hands, focusing on the reorientation of unknown objects around any specified axis. By utilizing tactile sensing, this approach ensures precise and adaptive manipulation without prior knowledge of the object's model. The proposed method was validated through preliminary experiments with the Allegro hand, demonstrating its potential efficacy in rotations around different axes.

Future research will focus on extending the proposed manipulation strategy to more complex movements. Additionally, exploring the application of this method to different types of robotic hands and diverse object shapes can broaden its practical applicability. Another promising direction involves improving the tactile sensing technology to provide higher resolution and more comprehensive feedback, facilitating even finer manipulation tasks.

References

[1] A. Montaño and R. Suárez, "Manipulation of unknown objects to improve the grasp quality using tactile information," *Sensors*, vol. 18, no. 5, p. 1412, 2018.

[2] S. Cruciani, H. Yin, and D. Kragic, "In-hand manipulation of objects with unknown shapes," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2020, pp. 8848–8854.

[3] M. Rakić, "Multifingered robot hand with selfadaptability," *Robotics and Computer-Integrated Manufacturing*, vol. 5, no. 2-3, pp. 269–276, 1989.

[4] R. Suárez and P. Grosch, "Dexterous robotic hand ma-i software and hardware architecture," in *International Conference on Intelligent Manipulation and Grasping*, 2004, pp. 91–96.

[5] J. Bütepage, S. Cruciani, M. Kokic, M. Welle, and D. Kragic, "From visual understanding to complex object manipulation," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 2, pp. 161–179, 2019.

[6] A. Montaño and R. Suárez, "Unknown object manipulation based on tactile information," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015, pp. 5642–5647.

[7] Z. Kappassov, J.-A. Corrales, and V. Perdereau, "Touch driven controller and tactile features for physical interactions," *Robotics and Autonomous Systems*, vol. 123, p. 103332, 2020.

[8] Z. Li, P. Hsu, and S. Sastry, "Grasping and coordinated manipulation by a multifingered robot hand," *The international Journal of Robotics research*, vol. 8, no. 4, pp. 33–50, 1989.

[9] J. Kerr and B. Roth, "Analysis of multifingered hands," *The International Journal of Robotics Research*, vol. 4, no. 4, pp. 3–17, 1986.

[10] R. D. Howe and M. R. Cutkosky, "Practical force-motion models for sliding manipulation," *The International Journal of Robotics Research*, vol. 15, no. 6, pp. 557–572, 1996.

[11] J. Hong, G. Lafferriere, B. Mishra, and X. Tan, "Fine manipulation with multifinger hands," in *Proceedings., IEEE International Conference on Robotics and Automation*. IEEE, 1990, pp. 1568–1573.

[12] T. Chen, J. Xu, and P. Agrawal, "A system for general in-hand object re-orientation," in *Conference on Robot Learning*. PMLR, 2022, pp. 297–307.

[13] T. Chen, M. Tippur, S. Wu, V. Kumar, E. Adelson, and P. Agrawal, "Visual dexterity: In-hand reorientation of novel and complex object shapes," *Science Robotics*, vol. 8, no. 84, p. eadc9244, 2023.

[14] I. Zaplana, H. Hadfield, and J. Lasenby, "Closed-form solutions for the inverse kinematics of serial robots using conformal geometric algebra," *Mechanism and Machine Theory*, vol. 173, p. 104835, 2022.

[15] (2018) Allegro robotic hand—wonik robotics. [Online]. Available: http://wonikrobotics.com/Allegro-Hand

[16] A. Montaño and R. Suárez, "Dexterous manipulation of unknown objects using virtual contact points," *Robotics*, vol. 8, no. 4, p. 86, 2019.