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Task execution combined with in-contact obstacle navigation by exploiting torque feedback of sensitive robots

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Abstract

Collaborative redundant manipulators are becoming more popular in industry. Lately, sensitive variants of those robots are introduced to the market. Their sensitivity is owed to the unique technology of integrating torque sensors into their joints. This technology has been used extensively for collision detection. Nevertheless, it can be used in other collaborative applications. In this study, we present a novel control method that uses the torque feedback at the joints to perform automatic adjustment of the self-motion manifold during a contact with surrounding obstacles, while allowing the user to control the robot at the end-effector (EEF) level. This makes the interaction with sensitive redundant manipulators more intuitive to users. Experimental tests on KUKA iiwa robot proved the effectiveness of the proposed method for navigating obstacles during a contact with robot's structure while keeping the precision in the task under execution.

Keywords: Collaborative robots; intuitive interfaces; torque feedback; redundancy; null space

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1. Introduction

Collaborative sensitive manipulators are becoming more popular in industry. Owing to their safety centered design, these manipulators are certified to work side by side with human coworkers. In addition, they are architectured to satisfy the requirements of the factories of the future. As such, their utilization comes hand in hand with the criterion of Industry 4.0, as it is expected to have humans and robots working in shared work spaces, collaborating with each others.

The introduction of integrated torque sensors into the joints of industrial manipulators had a major impact on safety capabilities of collaborative robots. Such technique allows compliant behavior of the robot (through control), also it provides the robot with high sensitivity in detecting collisions with the surroundings [1], including humans, a major safety requirement [2]. A representative example of sensitive robots are the KUKA lightweight series of manipulators. From the DLR Lightweight Robot LWR III [3, 4], to the KUKA LWR IV (research version) [5], and the current industrial sensitive manipulators iiwa 7R800 and iiwa 14R820 [6]. Owing to their sensitivity, these industrial robots are being used in various manufacturing domains including aerospace [7] and automotive industries [8].

While safety technologies for robots are evolving and maturing, challenges still persist in achieving intuitive interfaces that allow workers to interact and program a robot easily in a natural way. As a matter of fact, a skilled person with technical know-how is still required to program an industrial robot and put it into operation. As such, various research studies proposed intuitive solutions which allow natural interaction between humans and robots. In such a case, a worker without a (robotics-related) technical knowledge will be able to program and teach the robot intuitively. Yet, this field of study is still in its infancy, and is open for extensive research. Some of the proposed studies implemented virtual reality [9] and visual cues as a tool for facilitating robot programming and teaching. Other researchers utilized the force feedback for robot teaching. In [10] the authors presented the virtual tool method for kinesthetic teaching of robotic manipulators. In [11] the authors proposed a method for guiding the end-effector (EEF) of a manipulator precisely in Cartesian space. In [12] the authors presented a method for hand-guiding redundant manipulators in cluttered

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environments. In addition, various methods have been proposed to simplify the way in which industrial robots are programmed, either for increasing time efficiency on the factory floor, or for achieving systems that are more user friendly [13]. For example, in [14] the authors used gestures to control a robot in an industrial task.

In robotic manipulation applications, the use of redundant robots offer various advantages, where the extra degrees of freedom can be used to achieve many objectives including the avoidance of obstacles around the robot [15], avoiding singularities and joint limits during the movement [16], improving dynamical response [17], or minimizing energy consumption and improving dexterity [18]. Consequently, redundancy in manipulators has been used for performing various important tasks. Yet, the introduction of redundancy has made programming a redundant robot more challenging for workers, especially in cluttered environments, where the robot is moving between obstacles. As such, we introduce a novel solution, which allows a sensitive robot to adjust its redundancy automatically (through torque feedback from its joints) as it evolves in cluttered environment. This allows the redundant robot to avoid obstacles automatically during physical contact with them. Consequently, a worker can move the robot at the EEF level in the cluttered environment, while the redundancy is adjusted automatically upon contact. Such technique offers various advantages:

- Convenience: the proposed method makes jogging the robot in cluttered environments more convenient. In such a case, a possible contact is treated automatically, where the redundancy is adjusted by the algorithm without requiring an intervention from the user;
- Time efficiency: normally, when jogging a redundant robot at EEF level in cluttered environments, redundancy is adjusted by the user from a dedicated button in the teach pendant. In such a case, the jogging operation shall be aborted and then the redundancy is adjusted. Afterwards, the jogging operation is resumed again. In tight spaces, the previous procedure has to be repeated various times, resulting in time inefficiency due to the various interruptions of the jogging operation. In contrast, the proposed solution does not result in interruptions to the jogging motion, as such offering a time efficient solution;
- Intuitiveness: due to the automatic adjustment of the redundancy the proposed method is more intuitive than using a dedicated button in the teach pendant (traditional way);
- The method is also applicable for off-line generated path of EEF. In such a case, the robot is able to move on the path while adjusting automatically to external contacts, as shown later in the experiments section.

This article is organized into various sections. After the introduction, the proposed method is introduced in section II. In section III the mathematical formulation for the control strategy is derived. In section IV the proposed method is tested on KUKA iiwa 7R800 redundant manipulator. The article ends with the conclusion in section V.

Nomenclature

$\dot{\boldsymbol{x}}$	Cartesian velocity at EEF
$\boldsymbol{q}$	vector of joints angles
$\dot{\boldsymbol{q}}$	vector of joints angular velocities
$\dot{\boldsymbol{q}}_{ln}$	least norm solution of the joints angular velocities
$\dot{\boldsymbol{q}}_{n}$	projected angular velocities in the null space
$\mathbf{J}^{\dagger}$	pseudo inverse of the Jacobian
$\mathbf{A}$	joint space mass matrix
$\mathbf{C}$	joint space Coriolis matrix
$\mathbf{N}$	null space projection matrix
$\boldsymbol{\tau}_{ex}$	joint torques due to external contact forces
$\boldsymbol{\tau}_{r}$	vector of measurements from the joints torque-sensors
$\boldsymbol{\tau}_{dyn}$	joint torques due to motion of the robot

2. Proposed method

The proposed method is explained in snapshots in Fig. 1 (taken from the video segment in https://www.youtube.com/watch?v=wWOMALk4-HQ). The EEF of a redundant robot is controlled in Cartesian space with linear motion on a path generated off-line (also can be on-line jogging motion from an external motion command). An obstacle (metallic rod) is in the way of the robot, as shown in Fig. 1. During the motion and using the integrated torque sensors, the robot is able to detect a contact with the obstacle Fig. 1 (b). At the same time, the redundancy of the robot is controlled automatically and adjusted for performing in-contact obstacle navigation (using our proposed method), and only through measurements from torque sensors integrated at the joints, without requiring any external sensors. This results in a sliding motion of the robot structure on the body of the obstacle Fig. 1 (c,d,e,f). If the null space motion is not enough to navigate the obstacle, an emergency stop is initiated. Tests using KUKA iiwa robot demonstrate the effectiveness of the proposed method. The following section introduces the mathematical formulation of the control method.

3. Control strategy

The inputs to the proposed controller are:

- A motion command of the EEF in Cartesian space. It can be either an off-line generated path, or an on-line jogging command (from the teach pendant for example).
- Torque measurements from the integrated torque sensors at the joints of the robot.

Most industrial robots, including the KUKA iiwa 7R800 and 14R820, are controlled at the kinematic level, by streaming the joints reference positions or velocities to the robot. As such, the proposed control strategy operates at the kinematic level, it includes superimposing the angular velocities $\dot{\boldsymbol{q}}_{ln}$ that satisfy

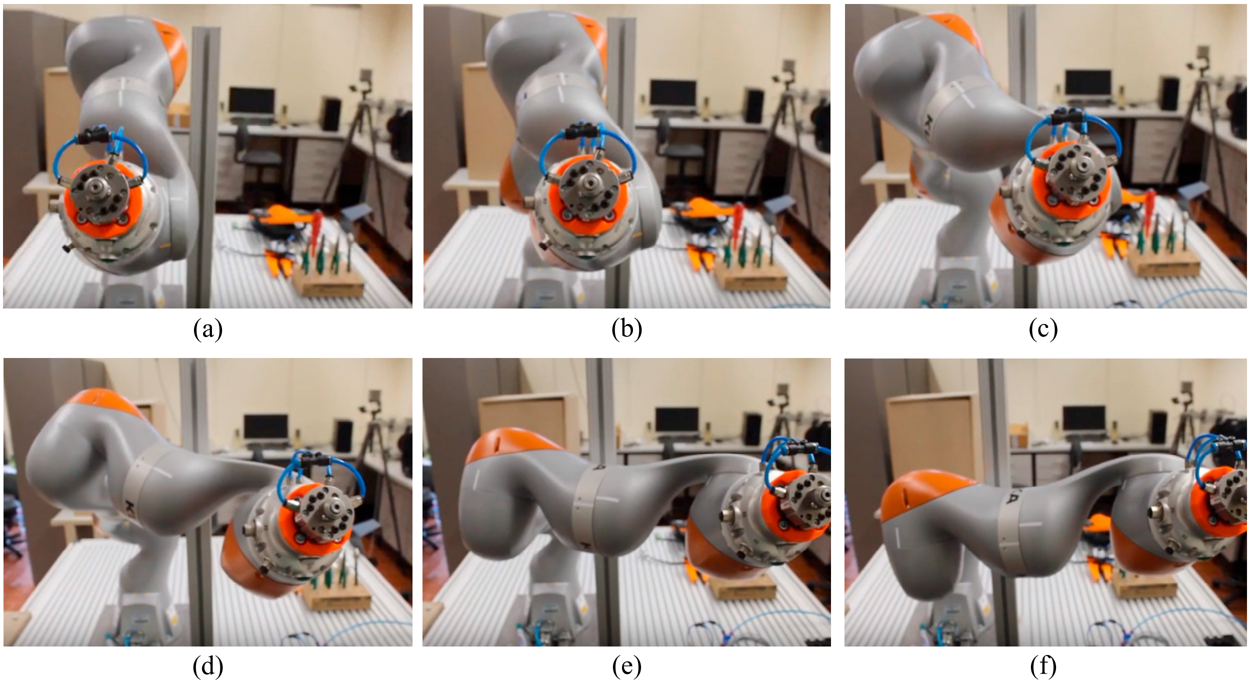
(a) (b) (c) (d) (e) (f)

Fig. 1. Snapshots of the robot automatically avoiding an obstacle (metallic rod) during contact while the EEF is moving on a pre-planned Cartesian path. (a) EEF starts moving on a line parallel to the Y axis of the base. (b) Robot structure comes into contact with the obstacle. (c,d,e) The robot slides with its structure on the obstacle while keeping the EEF on the linear path. (f) Robot reaches the end of the path.

EEF motion, with the angular velocities at the null space $\dot{\boldsymbol{q}}_n$ that satisfy the in-contact obstacle navigation. The mathematical formulas presented hereafter are kept generic. Thereby, the method is applicable for any sensitive robot possessing redundancy with respect to its required task.

3.1. Differential inverse kinematics

In the proposed method, the motion command of the EEF is defined by the linear and angular velocity vector $\dot{\boldsymbol{x}}$. Using differential kinematics [19] the corresponding angular velocities of the joints are calculated:

$$\dot{\boldsymbol{q}}_{ln} = \mathbf{J}^{\dagger}\dot{\boldsymbol{x}} \tag{1}$$

Where $\dot{\boldsymbol{q}}_{ln}$ is the least norm solution of the joints angular velocities, $\mathbf{J}^{\dagger}$ is the pseudo inverse of the Jacobian, and $\dot{\boldsymbol{x}}$ is the velocity of the EEF.

3.2. Joint torques and null space motion

Once a contact is initiated with the obstacle, extra torques due to contact forces $\boldsymbol{\tau}_{ex}$ start to appear in the joints:

$$\boldsymbol{\tau}_{ex} = \boldsymbol{\tau}_r - \boldsymbol{\tau}_{dyn} \tag{2}$$

Where $\boldsymbol{\tau}_{ex}$ is the vector of external-torque due to external contact forces, $\boldsymbol{\tau}_r$ is the raw torque measurements from the sensors at robot joints, and $\boldsymbol{\tau}_{dyn}$ are the torques due to robot's motion and gravity. The latter includes the torques due to (1) joints angular acceleration, (2) Coriolis/centrifugal effect, (3) friction at joints and (4) torques due to gravity, it is given by the equation:

$$\boldsymbol{\tau}_{dyn} = \mathbf{A}\ddot{\boldsymbol{q}} + \mathbf{C}\dot{\boldsymbol{q}} + \boldsymbol{f}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g} \tag{3}$$

Where $\mathbf{A}$ is the mass matrix of the robot, $\ddot{\boldsymbol{q}}$ is the vector of joints angular acceleration, $\mathbf{C}$ is Coriolis matrix of the robot, $\dot{\boldsymbol{q}}$ is the vector of joints angular velocities, $\boldsymbol{f}(\boldsymbol{q}, \dot{\boldsymbol{q}})$ is the torque vector due to Coulomb and viscous friction at the joints, and $\boldsymbol{g}$ are the torques due to gravitational effect and friction. In such a case, the precision of calculating $\boldsymbol{\tau}_{dyn}$ depends mainly on the precision of the dynamical model used to describe the manipulator's dynamics. If a tool is attached to the robot it shall be taken into consideration when calculating $\boldsymbol{\tau}_{dyn}$, where the inertial data of the tool, including its weight, enter in the calculation of $\mathbf{A}$, $\mathbf{C}$ and $\boldsymbol{g}$.

When it comes to KUKA iiwa robots, the Sunrise Controller calculates internally the vector of the external torques, the controller is also compensating for the tool attached to the flange, allowing the user to acquire the numerical value of vector $\boldsymbol{\tau}_{ex}$. In this study, we opted to use the KUKA Sunrise Toolbox [6], where we are able to retrieve the components of $\boldsymbol{\tau}_{ex}$ using a TCP/IP communication in MATLAB.

A proportional controller is utilized such that the torques-command vector is used to calculate the corresponding angular velocities $\dot{\boldsymbol{q}}_{ex}$:

$$\dot{\boldsymbol{q}}_{ex} = \mathbf{B}\boldsymbol{\tau}_{ex} \tag{4}$$

Where **B** is a diagonal matrix containing the proportional coefficients. Then, the component of the angular-velocity in the null space of the Jacobian [20] is calculated using null space projection matrix **N**:

$$\dot{\boldsymbol{q}}_{n} = \mathbf{N}\dot{\boldsymbol{q}}_{ex} \tag{5}$$

3.3. Control command

The total command used to control the robot is the sum of (1) angular velocity vector due to EEF motion command, (2) null space angular velocity vector, which allows the robot to slide on the obstacle:

$$\dot{\boldsymbol{q}} = \dot{\boldsymbol{q}}_{ln} + \dot{\boldsymbol{q}}_{n} \tag{6}$$

Depending on the way the robot is controlled, the control command can be established. Using the KUKA Sunrise Toolbox, the robot is controlled on-line by real-time stream of angular positions. For calculating the angular positions vector $\boldsymbol{q}$ the angular velocities vector $\dot{\boldsymbol{q}}$ is integrated for each time step $\triangle t$:

$$\boldsymbol{q} = \int_{t}^{t+\Delta t} \dot{\boldsymbol{q}} dt \tag{7}$$

Those angles are sent on-line to the robot controller, in this study using TCP/IP connection [6].

4. Experiments

The proposed method was applied on the KUKA iiwa 7R800 robot, a sensitive collaborative robot provided with torque sensors integrated into its joints. Fig. 2 demonstrates the proposed experimental setup, a video-segment showing the test is in `https://www.youtube.com/watch?v=wWOMALk4-HQ`, where the robot is moving the EEF on a linear trajectory generated off-line. At the same time there is an obstacle, a metallic pole in the way of the robot. During the motion, the robot structure comes into contact with the obstacle. If the proposed method for redundancy resolution is not used the robot keeps pushing with its structure against the obstacle causing joints-torques to increase in value and triggering an emergency stop. On the other hand, using the proposed method, the robot adjusts its configuration, by utilizing its redundancy, Fig. 3. As a result the robot is able to keep moving on the off-line generated path while navigating the obstacle during the contact until reaching the end of the path Fig. 4.

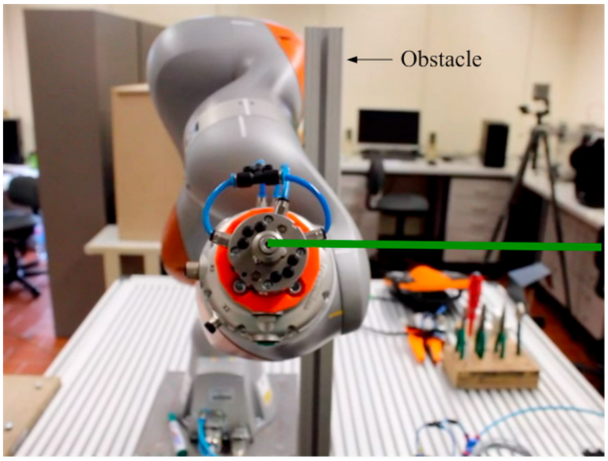

Fig. 2. Experimental setup: KUKA iiwa robot is in the home position, a metallic obstacle is near the body of the robot, the green line indicates the required path of the EEF.

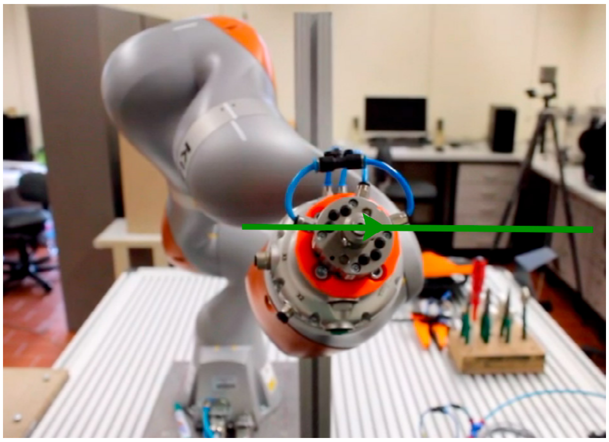

Fig. 3. The robot initiates contact with the metallic obstacle while moving the EEF on the pre-planned path.

During the test, the following data were recorded:

1. Torque vector $\boldsymbol{\tau}_{ex}$ due to external contact forces, Fig 5;
2. Joints angular positions, Fig 6.

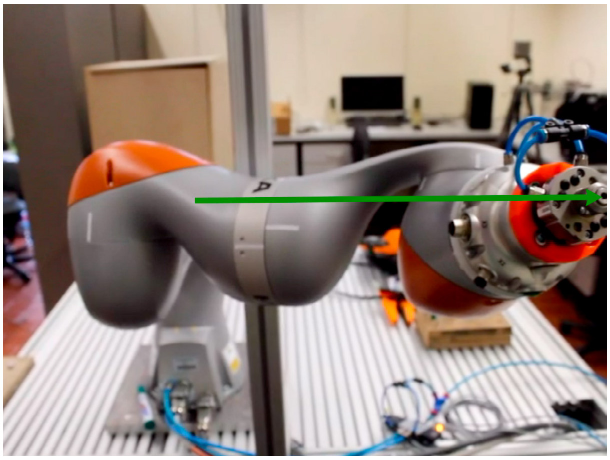

Fig. 4. Robot reached the end of the path successfully while navigating the obstacle.

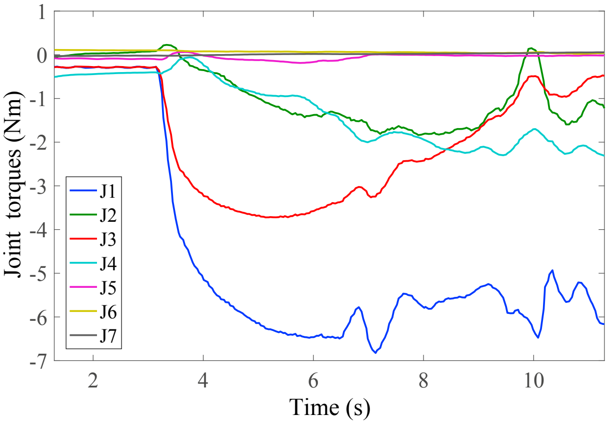

Fig. 5. Torque estimates due to external contact forces as acquired from the robot controller.

Qualitatively, the robot is able to navigate the obstacle during contact while performing the required task. Quantitatively, during its motion the robot touches the obstacle in Fig. 3. Fig. 5 shows the torques evolution with time during the test, when the contact is initiated the torques on joints one and three increase dramatically. Also, the torques on joints two and four increase but to a lesser magnitude. Using our control scheme this increase in torques cause a motion in the null space of the robot. The null space motion is also evident by the increasing rate of joint values in Fig 6. As a result, the robot slides on the obstacle while moving on the original path. The robot continues its motion (keeping the end-effector on the planned path) until reaching the goal successfully Fig. 4.

5. Conclusion

In this study we proposed a novel method for automatic redundancy resolution of the null space motion for redundant sensitive robots subject to contact with surrounding obstacles. The proposed method makes use of the integrated torque sensors in the joints of sensitive redundant manipulators, as such exploring their full potentiality. The torque measurements from robot joints are used for in-contact obstacle navigation. This is achieved by performing automatic motion in the null space, making the use of redundant manipulators more convenient and more intuitive for users. From tests carried out on KUKA iiwa industrial manipulator it is concluded that the robot manages to perform the desired path, moves in a natural way, while performing in-contact obstacle navigation in the null space.

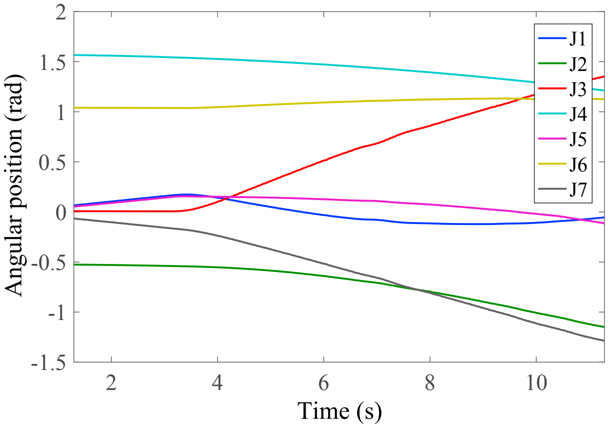

Fig. 6. Joint angular positions during the test.

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References

[1] K. Schroeder, M. Pryor, and T. Harden. On the use of joint torque sensors for collision detection in a confined environment. In *ANS 3 rd International Joint Topical Meeting on Emergency Preparedness & Response and Robotics & Remote Systems. Knoxville, TN*, 2011.

[2] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger. Requirements for safe robots: Measurements, analysis and new insights. *The International Journal of Robotics Research*, 28(11-12):1507–1527, 2009.

[3] G. Hirzinger, N. Sporer, A. Albu-Schaffer, M. Hahnle, R. Krenn, A. Pascucci, and M. Schedl. DLR's torque-controlled light weight robot iii-are we reaching the technological limits now? In *Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292)*, volume 2, pages 1710–1716 vol.2, May 2002.

[4] S. Haddadin, M. Suppa, S. Fuchs, T. Bodenmüller, A. Albu-Schäffer, and G. Hirzinger. Towards the robotic co-worker. In Cédric Pradalier, Roland

Siegwart, and Gerhard Hirzinger, editors, *Robotics Research*, pages 261–282, Berlin, Heidelberg, 2011. Springer Berlin Heidelberg.

[5] F. Flacco, T. Kröger, A. De Luca, and O. Khatib. A depth space approach to human-robot collision avoidance. In *2012 IEEE International Conference on Robotics and Automation*, pages 338–345, May 2012.

[6] M. Safeea and P. Neto. Kuka sunrise toolbox: Interfacing collaborative robots with matlab. *IEEE Robotics Automation Magazine*, 26(1):91–96, March 2019.

[7] D. Busson and R. Bearee. A pragmatic approach to exploiting full force capacity for serial redundant manipulators. *IEEE Robotics and Automation Letters*, 3(2):888–894, April 2018.

[8] J. Saenz, N. Elkmann, O. Gibaru, and P. Neto. Survey of methods for design of collaborative robotics applications-why safety is a barrier to more widespread robotics uptake. In *Proceedings of the 2018 4th International Conference on Mechatronics and Robotics Engineering*, pages 95–101. ACM, 2018.

[9] J. I Lipton, A. J Fay, and D. Rus. Baxter's homunculus: Virtual reality spaces for teleoperation in manufacturing. *IEEE Robotics and Automation Letters*, 3(1):179–186, 2018.

[10] G. Ferretti, G. Magnani, and P. Rocco. Assigning virtual tool dynamics to an industrial robot through an admittance controller. In *Advanced Robotics, 2009. ICAR 2009. International Conference on*, pages 1–6. IEEE, 2009.

[11] M. Safeea, R. Bearee, and P. Neto. End-effector precise hand-guiding for collaborative robots. In *Iberian Robotics conference*, pages 595–605. Springer, 2017.

[12] M. Safeea, P. Neto, and R. Bare. Precise hand-guiding of redundant manipulators with null space control for in-contact obstacle navigation. In *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, volume 1, pages 693–698, Oct 2019.

[13] P. Neto, N. Pires, and A. Moreira. High-level programming and control for industrial robotics: using a hand-held accelerometer-based input device for gesture and posture recognition. *Industrial Robot: An International Journal*, 37(2):137–147, 2010.

[14] P. Neto, M. Simão, N. Mendes, and M. Safeea. Gesture-based human-robot interaction for human assistance in manufacturing. *The International Journal of Advanced Manufacturing Technology*, pages 1–17.

[15] R.V. Patel and F. Shadpey. *3 Collision Avoidance for a 7-DOF Redundant Manipulator*, pages 35–78. Springer Berlin Heidelberg, Berlin, Heidelberg, 2005.

[16] A. Liegeois. Automatic supervisory control of the configuration and behavior of multibody mechanisms. *IEEE Transactions on Systems, Man, and Cybernetics*, 7(12):868–871, Dec 1977.

[17] J. Hollerbach and K. Suh. Redundancy resolution of manipulators through torque optimization. *IEEE Journal on Robotics and Automation*, 3(4):308–316, 1987.

[18] C. A Klein and B. E Blaho. Dexterity measures for the design and control of kinematically redundant manipulators. *The international journal of robotics research*, 6(2):72–83, 1987.

[19] P. Corke. *Robotics, Vision and Control: Fundamental Algorithms In MATLAB*, volume 118. Springer, 2017.

[20] B. Nemec, L. Žlajpah, and D. Omrčen. Comparison of null-space and minimal null-space control algorithms. *Robotica*, 25(5):511–520, 2007.