Article

HUMAN MOTION GUIDANCE USING VIBROTACTILE FEEDBACK IN DIRECT PHYSICAL HUMAN-ROBOT INTERACTION

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Abstract: A physical human-robot interaction (pHRI) task such as cooperative object manipulation between the human and robot, where the robot traditionally adopts its motion to the desired trajectory imposed by the human partner. However, certain areas in the workspace of the human-robot team can be unfeasible (inadmissible), which the human-robot team is unable to make any desired tasks. In particular, the human partner is usually unaware of the obstacles found in the environment, especially if they are not in the line of sight of the human. In addition, the human desired motion may result in the robot singular configurations. Using the wearable vibrotactile wristband device, the suitable feedback can be conveyed to the human partner by the vibration stimulus. Such that, the human-robot team is successfully avoided the obstacles (inadmissible area) and singularities. The work is carried out the three subtasks such as human motion guidance; human-robot team obstacle avoidance and human-robot singularity avoidance. The research work and the results showed to enhance the direct physical human-robot cooperation team.

Keywords: Haptics; human-robot interaction; vibrotactile feedback; obstacle avoidance; singularity avoidance; wristband device; 7 DOF manipulators.

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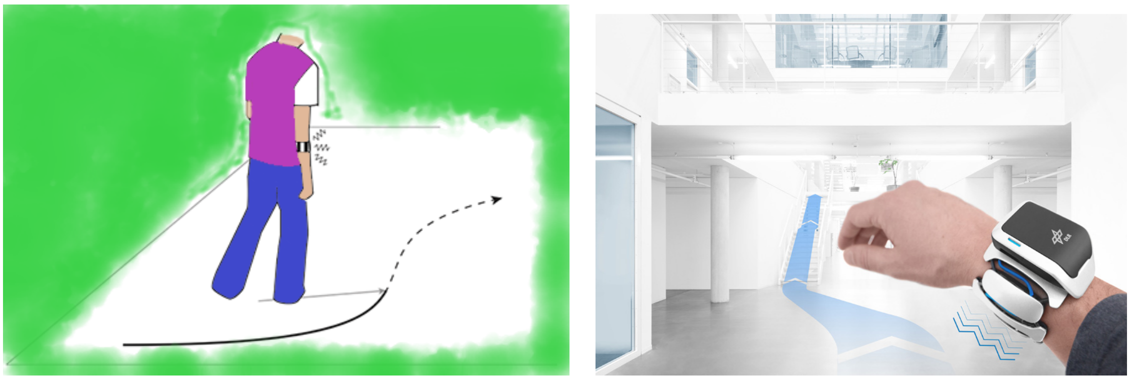
1. Introduction

A word *haptic* refers to a type of communication which uses the sense of touch. Haptic guidance has been used in various applications such as a guidance for the blinded people [26], medical field [17] and human-robot interaction [14,16]. In haptic one of the promising means of providing contact information to the operator with minimal cost and less complexity is vibrotactile feedback. The vibration signals are key events during interaction tasks and people make explicit use of this information. Also, the humans have highly specialized nerve endings for the perception of vibrations, which can detect vibrations to over 1 kHz in frequency and less than 1 micrometer in amplitude (Johansson, Landstrom and Lundstrom 1982).

The vibrotactile feedback is already proven in many of the guidance task research [17,26]. For instance, blinded people face many difficulties for finding way to their home or office in the modern complex environment (i.e. buildings, cars, shopping malls and narrow roads in streets) and the vibrotactile wristband is used to assist the blinded people more precisely than a walking stick in the modern complex world Fig. 1(a).

Many research studies [12,19] have shown that vibrotactile guidance improves performance when compared to other modes of feedback such as audio or visual, particularly in noisy environments [17]. Another practical advantage of vibration that it is perceivable through clothes and can be easily embedded into everyday wearables, like a bracelet, belt or insole [21]. The vibrotactile stimulation allows for displaying information to the user without annoying others and also it is helpful, where the users have unclear visual and acoustical information in complex working scenarios. In this work, we evaluate usage of the vibrotactile feedback in the context of direct physical human-robot interaction,



(a) Blinded people guidance (b) Vibrotactile wrist band device at DLR

Figure 1. Vibrotactile feedback guidance usage in the real life scenarios

where the feedback is provided through a wearable vibrotactile wristband [12]. Also, the device guidance is used to evaluate in multiple tasks such as *attentional guidance*, *movement guidance* and *spatial guidance*, paradigms of spatial guidance are given directional clues while walking or guiding the human hand and leg in the desire directions [21]. However, this work is focused on the *attentional guidance* and *movement guidance* in the HRI.
A vision of this research work is to enhance human capabilities when in collaboration with a robot. The vibrotactile feedback in a human-robot team interaction (HRTI) task which increases the human knowledge in the human-robot cooperation (HRC) tasks. Particularly, the robot and human team are cooperatively carrying an object from the initial to the goal position, then the total team has to solve many problems throughout the trajectory for a feasible solution. Our research study is solved some of the challenges during the cooperative task with the help of the wearable vibrotactile wristband device (WB). Additionally, the role of the haptic feedback (HF) in HRTI is very important because the HF gives the sufficient information to guess about the working environment conditions in a real-time scenario and it is desirable to devise valuable methods of effective HRI.

1.1. Problem statement

In this research work, the physical human-robot team (pHRT) carries an object from the initial to target position. "Figure. 2 " shows the cooperative manipulation of the object between the human and robot. The pHRI team has to overcome some challenges which are stated below.

- Human motion guidance towards desired trajectory/motions, which means the human velocity guides to desire velocity $v_h \rightarrow v_h^d$.
  where v_h is the actual human velocity and v_h^d is the desired human velocity in pHRI.
- An obstacle avoidance of HRT in the working environment, where human is unaware of the obstacles and a robot has knowledge of the obstacles.
- Avoiding singular configuration of the robot, when the human makes the manipulation outside of the robot capability space (i.e. any translational or rotational movements) which leads to singularities in pHRTI.

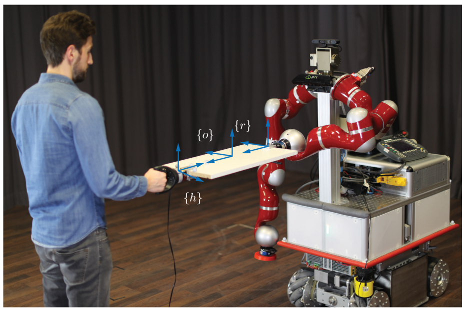


Figure 2. Human and robot cooperatively manipulating an object for given task, this is called as direct physical human-robot interaction task

1.2. Outline of the work

The paper has the following structure: Section 1 already mentioned about the introduction, Section 2 literature overview of the previous related work. Section 3 formalizes the solution of a problem, Section 3 describes design of the solution of this work. Section 4 formalizes the constraint kinematics and dynamics of cooperation manipulation modeling equations. Section 5 describes methodology and the proposed approach which motivates it theoretically with subtasks, Section 6 describes the experimental devices and equipments which used in this work, Sections [7, 8 9] describe about the experimental design, experimental analysis and experimental results respectively and then followed by discussion, materials, conclusion and future work.

2. Related Work

2.1. Phyical human-robot interaction

The physical robot interaction (pHRI) is one of the most interesting topics in the small-scale industry and the home assistance, where a user needs assistance to share the workload. More importantly, the disable people must need help for fulfilling the everyday activities, where one should not able to do things alone. Indeed, when cooperative manipulation tasks in the pHRTI, there should need a fine control scheme, efficiently estimated parameters and appropriate modeling strategies these are mentioned explicitly in [4]. Certainly, a human works with robotic manipulators, such that the robotic manipulators are dynamic systems and interact with other dynamic systems (i.e. human or objects). Thus during interaction with the human, it should somehow accommodate constraints which impose by the human and therefore the impedance controllers come into the act and its scenario is shown in [5] and also the concept and its working principle clearly explains in [6,7]. Additionally, the cooperative dynamics and kinematics of the human with a robot and the role of effort sharing between the human and robot with influence by the internal and external wrenches are stated in [8,9]. However, in our experiments, the human has only contact with robot's end effector and hence, the Cartesian impedance control with redundant manipulators (7 DOF) for human-robot (HT) cooperation is explained systematically in [10,12].

2.2. Vibrotactile in the human-robot interaction

Accordingly, the wristband is easily wearable and portable to carry and would be integrated into the HRT over vibrotactile (VT) feedback which showed [13–15]. The WB guides and assists the human in many rescue operations [13] and this would progress in the military and emergency services, where the robot could access very small and dark areas. The vision and audio modalities certainly might not efficient in case of reduced visibility or high noise environment. Indeed, a promising way to guarantee effective communications between the robot and human in a team is the vibrotactile wristband device. In [14] the human-robot (HR) formation control via visual and vibrotactile WB, here the human acts as a leader and multiple robots follows the human and this regard WB guides the human along trajectories that are feasible for the team by warning the user's arm through the VT feedback.

Additionally, the VT feedback is used in the grasping tasks [16], which the human intention carry through the flex sensors glove while the vibrations actuators place on fingers' tip for sensing of grasping when the humanoid robot grasp an object, such that the VT sense on fingers' tip feels like a grasping force, this would be pioneer to the effective HRTI.

Furthermore, the cooperative human-robot tasks are shown in [14,15], where the group of robots which follow the human for the fulfillments mutual cooperation and the mobile robot steer the human from the initial to final position respectively. In [15] the robot guides the human when a large deviation with respect to the planned trajectory and this leads to a cooperative interaction when there is a situation the human and robot task align with orientation.

In summary, the audio and visual feedbacks are better at translation movement tasks [12,19] when clear and quiet environments through the VT guidance has shown better results for rotational movements and particularly at the noisy environments the only VT feedback is an intuitive method. The VT perception in real scenarios are studies on the foot, waist and wrist [21], the foot and hand have a high sense of perception when compare to other body areas. On the other hand, the vibrotactile at the foot reduces visual attention and also potentially reduces the stress of the user and in contrast, the foot loses the sense of perception with sudden or instant movements which are clearly explained [21]

3. Design of the solution

A rigid object is transported from the initial to goal position with the human and robot as a team, where the human has taken part in the cooperative manipulation along with a robot. On the other hand, a human is unaware of the desired goal location obstacles and robot singularities during the manipulation. The object's dynamics and kinematics are influenced by the human and robot team together throughout the initial to the goal position. Such that, pHRTI dynamics and kinematics relationships are calculated to guide the human in a team. Therefore, the three main challenges are solved with various approaches in this work and these approaches are stated in the following.

- Human guidance towards to the desired motion which would help to the human for achieving an intuitive motion in the mutual cooperation tasks, where the VT feedback WB guides the human for a feasible solution and also gives the directional clues according to human excited motions and leads towards the desired goal location.
- A qualitative real-time collision detection technique is used to overcome the obstacle avoidance and blocked areas in the pHRTI workspace, where human gets the information of obstacles by the vibrotactile WB device with this information human can avoid the obstacles/inadmissible area.
- The human need to be aware of the robot singularities during the cooperative manipulation, where the appropriate calculation of manipulability ellipsoid (ME) and the suggested information of effective manipulation directions are transfer by WWB to human. The WWB guides the human with the vibration stimulus in order to avoid the singularities for the intuitive cooperation task in pHRTI.

As well as, the robot transforms the information to the human by wristband (WB) device. During the cooperative task in this work, the vibro-motors (VM) produces the vibrations on the human wrist and the human perceives the sense of vibrations by WWB (wearable wristband). These vibrations are made the human to adjust the pose of manipulation and directional movements in the pHRTI workspace. Hence, the pHRTI achieves the objective of our work like trajectory guidance, the obstacles avoidance, and the singularities avoidance through Vibrotactile feedback (VTF), these VTF signals are produced according to the commands by the human-robot team (HRT).

4. Constraints' Formulation

This section is explained about cooperative manipulation of a commonly carried an object between the robot and human arms agents.

4.1. Cooperative manipulation kinematics

The cooperative manipulated object is assumed a rigid and the grasps of the human and robot end-effector are assumed to be rigidly connected to the object. Let us consider a coordinate frame of human $\{h\}$ robot effector $\{r\}$ and world/reference $\{w\}$, the cooperatively manipulated object and coordinate system is represented as depicted in Fig 3. The end-effector pose is stated by

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$$\mathbf{x}_i = \begin{bmatrix} \mathbf{p}_i \\ \mathbf{q}_i \end{bmatrix} \tag{1}$$

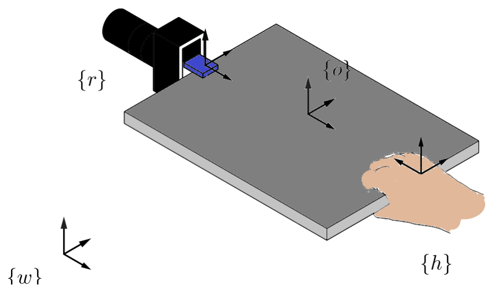


Figure 3. Human on one side and the robot is other side manipulating an object with human frame $\{h\}$, robot frame $\{r\}$ and reference/world frame $\{w\}$

where $\mathbf{x}_i \in SE(3)\ \forall i \in h, r$ which containing the translation and orientation of the robot/human $\mathbf{p}_i \in \mathbb{R}^3$ and $\mathbf{q}_i \in SO(3)$ in world frame respectively. The orientation is represented by the unit quaternion $\mathbf{q}_i = \left[\eta\ \epsilon^T\right]^T$, where $\eta \in \mathbb{R}$ is the real part and $\epsilon \in \mathbb{R}^3$ is the imaginary part. A rotation matrix matrix $\mathbf{R}(\mathbf{q_i}) \in \mathbb{R}^{3\times 3}$ of the quaternion $\mathbf{q}_i$ is defined as $\mathbf{R}(\mathbf{q_i}) = (2\eta_i^2 - 1)\mathbf{I}_3 +\ 2\mathbf{S}(\epsilon_i\ + 2\epsilon_i\epsilon_i^T)$ with $\mathbf{S} \in \mathbb{R}^{3\times 3}$ as a skew-symmetric matrix.

The twist of the human/robot is defined as

$$\dot{\mathbf{x}}_i = \begin{bmatrix} \dot{\mathbf{p}}_i^T & \boldsymbol{\omega}_i^T \end{bmatrix} \tag{2}$$

$\dot{\mathbf{x}}_i \in se(3)$ is a six-dimensional vector composed by the linear velocity $\dot{\mathbf{p}}_i = \mathbf{v}_i \in \mathbb{R}^3$ and angular velocity $\boldsymbol{\omega}_i \in \mathbb{R}^3$.

Similarly, the linear and angular accelerations of the human/robot.

$$\ddot{\mathbf{x}}_i = \begin{bmatrix} \dot{\mathbf{v}}_i^T & \dot{\boldsymbol{\omega}}_i^T \end{bmatrix} \tag{3}$$

The position and orientation of the human and the robot express in the world frame $\{w\}$ are represented by

$$\mathbf{p}_h = \mathbf{p}_r + \mathbf{R}(\mathbf{q}_r)\ {}^r\mathbf{r}_h \tag{4}$$

$$\mathbf{q}_h = \mathbf{q}_r \otimes {}^r\mathbf{q}_h \tag{5}$$

where the relative kinematics is represented by ${}^{r}\mathbf{r}_h \in \mathbb{R}^3$ as the relative displacement of $\{h\}$ with respect to $\{r\}$ and ${}^{r}\mathbf{q}_h$ as the relative orientation of $\{h\}$ with respect to $\{r\}$, however the symbol $\otimes$ denotes the quaternion multiplication.

Differentiation of the equation (4) and the object grasped rigidly by the human and the robot end-effector, as a result the relative displacement of human with respect to robot end-effector ${}^{r}\mathbf{r}_h =$ const. yields as

$$\dot{\mathbf{p}}_h = \dot{\mathbf{p}}_r + \boldsymbol{\omega}_r \times \mathbf{r}_h \tag{6}$$

Differentiating equation (6) again leads to

$$\ddot{\mathbf{p}}_h = \ddot{\mathbf{p}}_r + \dot{\boldsymbol{\omega}}_r \times \mathbf{r}_h + \boldsymbol{\omega}_r \times (\boldsymbol{\omega}_r \times \mathbf{r}_h) \tag{7}$$

Similarly,the relative orientation between the human with respect to the robot is constrained, i.e. ${}^{r}\mathbf{q}_h =$ const. and differentiation of (5), then the angular velocity

$$\boldsymbol{\omega}_h = \boldsymbol{\omega}_r \tag{8}$$

Differentiation of (8) again, the expression of the relative angular acceleration

$$\dot{\boldsymbol{\omega}}_h = \dot{\boldsymbol{\omega}}_r \tag{9}$$

4.2. Cooperative manipulation object dynamics

The equations of motion of a rigid object are derived by applying Lagrangian mechanics, where the object's kinetic energy is

$$\mathbf{T}_o = (1/2)\dot{\mathbf{x}}_o^T \mathbf{M}_o \dot{\mathbf{x}}_o \tag{10}$$

Also, the potential energy is represented by

$$\mathbf{U}_o = m_o g^T \mathbf{p}_o \tag{11}$$

with $\mathbf{M}_o = diag\,(m_o \mathbf{I}_3, \mathbf{J}_o)$, where $m_o \in \mathbb{R}$ and $\mathbf{J}_o \in \mathbb{R}^{3\times 3}$ are the object's and inertia matrix respectively, $g \in \mathbb{R}^3$ is the gravity vector and for simplicity omit the explicit indication of dependencies. The equations (10, 11) are derived the Lagrange equations which yields the object dynamics with respect to its center of mass.

$$\mathbf{M}_o \ddot{\mathbf{x}}_o + \mathbf{C}_o(\mathbf{x}_o, \dot{\mathbf{x}}_o) = \mathbf{u}_o \tag{12}$$

where $\mathbf{C}_o = [-m_o g \quad \boldsymbol{\omega}_o \times \mathbf{J}_o \omega_o]^T$ is the Coriolis matrix and $\mathbf{u}_o$ is the total object wrenches with $\mathbf{u}_o = [\mathbf{f}_o^T, \mathbf{t}_o^T]^T$, with $\mathbf{f}_o \in \mathbb{R}^3$ is the force and $\mathbf{t}_o \in \mathbb{R}^3$ is the torque acting on the object by individual human and robot.

5. Methodology

In this section we propose a control law and formalize the application problem of cooperative carrying the object.

5.1. Human guidance in pHRTI (subtask-1)

This task is conducted with the human and robot carrying the object from initial to the goal position. Where the human is not aware of the final location/place. This problem is solved by the guided clues of the vibrotactile feedback, this information which would assist the human to move to the final location/place. The objective of this task is to enhance the communicational information towards the human side in the pHRT. Once human feels vibrational directions then he/she manipulates the common object in those perceived directions. Such that the human awareness about the direction to reach the goal position. Therefore, the information of directional guidance is

carried by the wearable wristband (WB) on user's wrist for guiding the common object.
The HRT team moves from the initial to goal position with the object, here the robot (the robot in HRT) moves according to the human excited motions. Then the WWB device produces vibrotactile stimulus on the human wrist according to the human excited directions to desired directions. In this task, the wristband gives four directional clues like left, right, up and down with four motors in the 2D space. The WWB covers different directional clues with the different amplitudes on four motors according to the human excited directional motions. For instance, the human guidance in the right direction of his/her coordinate frame then the right-sided motor on wristband gives stimulus, while the human moves in diagonal motion then two motors stimulus with different amplitudes according to the human wrist positions. By this influence of vibrotactile haptic feedback to the human wrist, the human knows the directional movements of the HRT in cooperative tasks. This human guidance leads to the intuitive cooperative manipulation between the human and the robot.

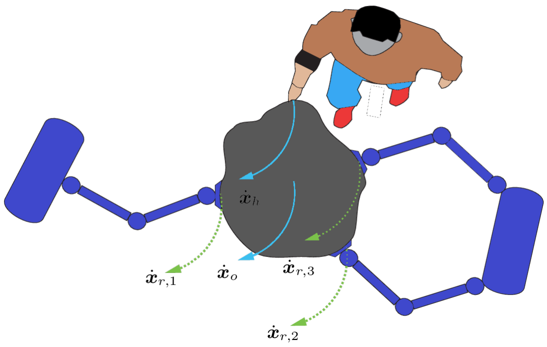


Figure 4. The human-robot team is cooperative manipulation an object which moving in the workspace and the WB devices guiding the human in human excited motions.

The human excited position $\mathbf{x}_h$ and velocity $\dot{\mathbf{x}}_h$ in the human-robot team (HRT) which leads the object velocity $\dot{\mathbf{x}}_o$ and robot velocity $\dot{\mathbf{x}}_r$ according the section (4). Here the human velocities/positions are the input for calculating appropriate amplitudes gain for the vibro-motors. The WB suggests the human moves in desired motions with four vibration motors on the wrist, which give directions for the feasible path or goal position. The vibrotactile warn signals are set to calculate the point-to-point on the desired trajectory. Consequently, the four motors guide the human in the up, down, right and left directions respectively.

5.1.1. Calculated VM amplitudes for subtask-1

In this experiment, the desired amplitudes are calculated according to the human velocities/positions $\dot{\mathbf{x}}_h$ in the 2-D plane (X-Z plane). For simplicity calculations and avoid noisy input data, in this experiments we are taken the real-time human positions $\mathbf{x}_h$ for input data. The four motors amplitudes are stated like right-left motors are used for X-plane (both positive and negative directions) motions and, the up-down motors are used for Z-plane motions. Therefore, taking the human positions during a task and this information is used to calculate the vibrotactile directional clues for each time step.
These real-time human positions are used for the calculation of specific amplitude gains for vibro-motors. Therefore, the motors are stimulated according to the calculated human directional motions in which the suitable vibrations are received to the human by the wearable WB device throughout the cooperative task in pHRTI.

Finally, the objective of this experiment is to find out the vibrotactile feedback would help to the human for better information in the loop of the human-robot interaction (HRI). Therefore, comparing the evaluation results of the pHRI with vibrotactile feedback. The evaluation results are considered to find out the performance of VT feedback in pHRTI for cooperative manipulation tasks.

5.2. Human guidance for avoiding the obstacles in pHRTI

The second subtask of our work is the pHRT obstacle avoidance when there is the human excited motions lead the HRT towards the obstacles. Furthermore, the pHRTI cooperative tasks are failed to fulfill the desired task. Therefore, the experiment is conducted for HRT with vibrotactile feedback (VTF) and these vibrations alarm the human when the obstacles are near to the HRT. Moreover, the WWB device steers the human to get out from the obstacles area and besides it also drives the towards the feasible trajectory/path for reaching the goal location. Figure. 5 shows an overview of this experiment with the human and robot manipulating an object in the obstacles/inadmissible area during the pHRTI task.
In this experiment, the foremost thing the robot must detect the obstacles around the human-robot team with the help of sensors which are mounted on the human hand. In this experiment, we are considered the obstacles/inadmissible area in 2D space for a limited degree of freedom of vibrotactile wristband device.

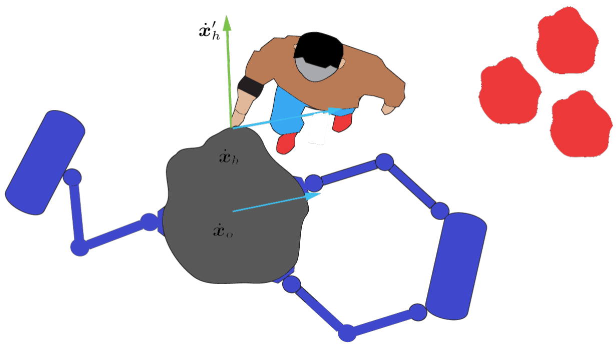


Figure 5. Human-robot is cooperatively carrying an object and human unaware of obstacles which robot detects the obstacles and give information to the human by the wearable wrist band device with vibrotactile feedback.

5.2.1. Calculated VM amplitudes for subtask-2

In this experiment, we are used four vibro-motors (i.e. right, left, up and down directional clues) due to limited directional clues of the wearable wristband device made some assumptions on obstacles (i.e. obstacles are in the 2D plane). The right and left vibro-motors are given vibrotactile information towards user's right and left repulsive directions, similarly up and down vibro-motors are given vibrotactile information towards the user's up and down repulsive directions. Therefore, the user can move the object in the VT directional clues. The minimum (i.e. threshold) distance is fixed between the obstacle and the human for produce VT feedback, where the human could free to choose his/her the directional movements up to less than minimum threshold distance from obstacles. Once the human comes closer to the obstacle (i.e when the human reaches the threshold distance) then the VT feedback starts to guide away from the obstacles in the repulsive feedback way. The right and left vibro-motors amplitudes are calculated according to the angle of direction between the human and the obstacles in the workspace. For instance, when the human angle greater than the obstacle angle with respect to fixed coordinate frame, then the left vibro-motor of WB gives amplitudes which guide the human to drive away (i.e guides opposite side of the obstacle) from away from obstacle, if the human angles less than obstacle angle then right vibro-motor gives amplitude signals on user's wrist. Similarly, the Up and down vibro-motors activate according to the human position with respect to the obstacle. In this way, the human does have knowledge about the obstacles during the cooperative manipulation tasks and make further motions for the feasible solution.

5.3. Human guidance for avoiding the robot singularities in cooperative task

The third subtask of the work is based on singular configurations in HRT, when the human and robot are cooperatively manipulating the object, however, the robot cannot perform all translational and rotational tasks as for the user's desire.

Therefore, calculation the capability area (workspace) of the robot manipulators helps to give the amplitudes of the wristband. When the human desired motions leads to robot singular configuration, the human can perceive warn signals on the wrist and able to avoid those particular movements which lead to pHRTI singularities. The "Fig. 6" shows the robot manipulators with limited manipulation space of manipulator, where the robot cannot perform the cooperative task with a human.

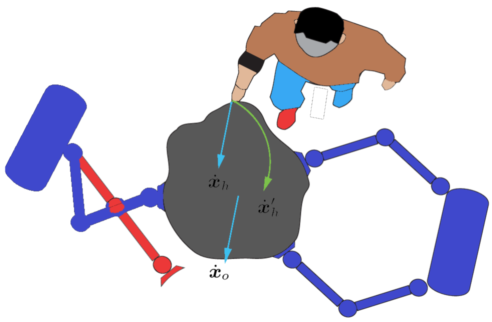


Figure 6. HRT cooperatively carrying an object in the workspace,where limited link of manipulator some excited configurations of human give singularities in task space

5.4. Manipulability Ellipsoid

Firstly, to avoid the singularities one should know about the maximum manipulating capability of the robot's manipulator in both the position and orientation perceptively. This concept is first introduced by Yoshikawa et al. [25]. Moreover, the robots are used in the cooperative tasks are redundant and null-space movement can be made to manipulator in an appropriate configuration. However, the robot's manipulator capability space is limited and our method can intuitive for the better cooperative task.

Where the ME is defined in the Cartesian space variables and must satisfy the following condition.

$$\mathbf{v}^T \cdot \mathbf{J}^{-T} \cdot \mathbf{J}^{-1} \cdot \mathbf{v} \leq 1\,, \tag{13}$$

where $\mathbf{v} \in \mathbb{R}^m$ is the velocity vector, $\mathbf{J} \in \mathbb{R}^{m \times n}$ the Jacobian matrix. and n is the number of joints of the manipulator.

A Manipulability ellipsoid can stated [25] by scalar value W is defined by

$$W = \sqrt{\mathbf{det}(\mathbf{J}\,\mathbf{J}^{\mathbf{T}})}\,, \tag{14}$$

The schematic diagram of the manipulability ellipsoid **(ME)** for the 7 DOF is shown in "Fig. 7".

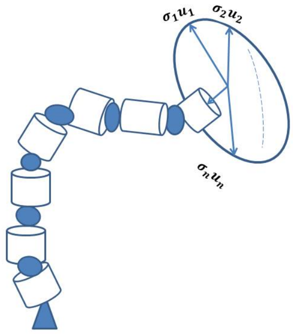


Figure 7. Schematic of 7DOF manipulability index

The equation is introduced in ((14)) is the volume of an ellipsoid and when it goes zero then the singularities take place in the workspace. In order to avoid those values, the manipulators must have to know the better direction of motion. Hence, the calculation of the direction which maximizes the capability of the position and orientation of the end effectors. In particularly, finding the eigenvalues of the Jacobian matrix 14 and that eigenvalues reflects the major and minor axes for manipulation and σ_1 is the major axis in the Fig. 7 and can be lead to find the best direction in the ellipsoid. However, the calculation of eigenvalues of the Jacobian matrix in the pHRTI is not possible directly because the robotic manipulator has 7 DOF and finding the determinant for the non-square matrix is complicated such that, the method of using **single value decomposition** (SVD) is introduced to calculate the eigenvalues. Therefore, the robot alarm human when the human violates the bounded ellipsoid.

5.4.1. Calculated VM amplitudes for subtask-3

This experiment is conducted to ensure that, the VT feedback also helpful for providing the knowledge of robot singular configurations to the human in CM tasks. However, the manipulator has limited links length, it is not intuitive to move in some directions (particularly when the robot's manipulators stretched out totally). Due to the robot's limited capability space (i.e. limited manipulator's link length), the robot end-effector makes unreachable configurations at some directions and those lead the HRT into singularities. Within the capability (also called as manipulability) space the robot able to make good pose and orientation configurations. Then the effective calculation of manipulability index (MI) value by robotic manipulator's Jacobian matrix. The MI shows the manipulability efficiency for task space configurations in pHRTI. Therefore, the efficient task space velocities are calculated to make the significant and high index value. Moreover, the calculated task space velocities are directly proportional to the vibro-motors amplitude gains. Indeed, by calculating the best directions of end-effector which maximize the equation (14).
The end-effector's velocities (in X-Z plane) are calculated in the direction towards the maximum eigenvalue (i.e. major axis) of manipulability ellipsoid. Therefore, the amplitudes are produced on user's wrist according to required end-effector's direction to maximize the index value (14). This suggested amplitudes are guided the human by the WWB device, which the human manipulation movements restrict into the admissible area of the HRT workspace. The human guidance is produced according to the stimulus of WWB device.

6. Experimental Device and Equipments

The framework for this experiment consists of two robotic manipulators, however, only one manipulator is used for the experimental task. The manipulators that grasp the object rigidly at one end and with human user on other end.

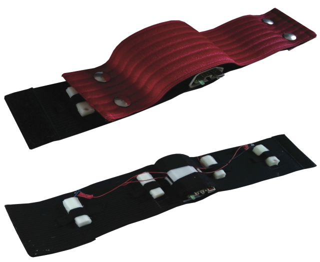
A robotic manipulator is composed of links connected by joints to form a kinematic chain. The links are individual rigid bodies that may have relative motion with respect to all other links. The links are connected by a joint where their relative motion can be expressed by a single coordinate frame. The robotic manipulator are 7DoF KUKA LWR 4+ lightweight robots. These robots are specially designed for mobility and interaction with a priori unknown environments and with humans. The robots have joint torque sensors in each joint and redundant position measurement (on motor and link side). The type of end-effector is chosen for the purpose of the task (in our case this tightly connected to object). The end-effectors used in our framework are moved in both translational and rotational tasks, and maintain the stable contact with the object. Here, the data is collected from force-torque sensors, between the last link and the end-effector to provide information about the forces and the moments applied on the object in the task space.

The motion of the hand and the inadmissible area is obtained from a marker-based motion tracking system, which is called as **Qualisys** [27]. The Qualisys motion capture system operates with motion capture cameras, QTM software and other integration peripheral hardware.

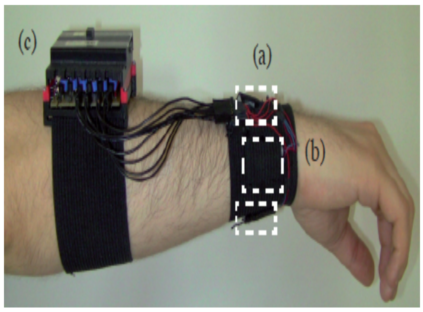
The motion capture system play important role in real-time data collection for experimental tasks. The sampling frequency used 1 KHz for the control part and 0.1 kHz for the Qualisys motion tracking system and wristband band device.

6.1. Overview of the vibrotactile wristband device

The VT wristband device (WD) was developed at University of Siena, it can be worn on a wide range of arm diameters while battery power and a wireless control interface contribute to unrestricted movement capability and user convenience. The WB device is used in this work has similar working principle to the *VibroTac* is a vibrotactile feedback device which was developed at the German Aerospace Center (DLR) [12].



(a) vibrotactile bracelet



(b) placement of the wearable vibrotactile wristband on human hand

Figure 8. (a) An overview of the proposed vibrotactile wristband using in this work. It consists of 4 actuators which equally displaced on the wearable bracelet and Arduino communication board in adjusted in the bracelet. (b) show the position of the wristband and its equipment on the human hand

The wearable vibrotactile haptic wristband Fig. 8(a) (the wristband device is used in this work) consists of 4 motors with 9mm vibration motor [13] with a vibration frequency range of $100 - 280$ HZ, an Arduino Pro Mini **3.3V** board, a RN42 Bluetooth 2.1 antenna, and a $\mathbf{3:3V}$ LiPo battery, mounted inside the pole. The wearable wristband WWB is placed on the

user's hand according to Fig. 8(b). The four cylindrical vibro-motors of WWB device are placed in the L (left), R (right), U (up) and D (down) directions of user's wrist and these motors are independently controlled via an external PC using with the Blue-tooth communication system. Figure.(8(b)) shows the placement of the WBD on user's wrist and hardware kit is placed on the human arm.

Since in our setup the haptic feedback provides to the human with indicative information about the constraints on $\dot{\mathbf{x}}_h$ velocities, four vibrating motors are utilized to independently warn or guides the user in an appropriate direction. The vibro-motors are stimulated according to the given amplitudes by the HRT. However,the WBD can use on any hand's wrist (i.e. right hand or left hand) and there is no evidence for the difference of perceptions among the left and right human hand.

7. Experimental Design

The aim of the user is to investigate the performance of vibrotactile wristband in direct physical human robot interaction team. These experiments are conducted individually for all the three sub-tasks and evaluated separately according to the obtained results.
The first experimental evaluation is done with three participants with three trails each. The task is given to pick an object and place another desired location, where with mass of the object **3.14** kg. Subsequently, the duration of the task is independent on the user, human can free to choose how fast or slow to perform the task. For the all experiments, the human operator uses wearable wristband haptic device on the right arm.
The duration is calculated as the difference between the end of the task and the beginning of the task.

$$Duration_i = Time_{end} - Time_{start} \tag{15}$$

Where the duration of time (15) is useful only in the first subtask evaluation and other two subtasks is not much useful.

Impedance Controller

The KUKa LWR4 impedance controller with inertia reshaping and the dynamic model of the robot has the form

$$\mathbf{M}(q)\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\ddot{\mathbf{q}} + \mathbf{g}(q) + \boldsymbol{\o}_f = \boldsymbol{\o}_c + \mathbf{J}^T(q)\mathbf{F}_{ext} \tag{16}$$

where $q \in \mathbb{R}^n$, with n=7, is the vector of joint variables, $\mathbf{M}(q)$ is the inertia matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\ddot{\mathbf{q}}$ is the vector of Coriolis/centrifugal torques, $\mathbf{g}(q)$ is the vector of gravitational torques, $\boldsymbol{\o}_f$ is the vector of friction torque, $\boldsymbol{\o}_c$ is the vector of control torques, $\mathbf{J}^T(q)$ is the robot Jacobian, and $\boldsymbol{\o}_{ext} = \mathbf{J}^T(q)\mathbf{F}_{ext}$ is the joint torque resulting from external force and moment $\mathbf{F}_{ext}$ applied to the end effector. The control strategy is designed to perform tasks in cooperation with humans. The operator in this work interacts with the robot by grasping the end effector (i.e the rigid object is place between human and robot's end effector) and moving it along the human excited motions. Hence, the external force is applied by th human to make cooperative manipulation in the experiments and $\mathbf{J}(q)$ Jacobian relating the joint velocities to the end effector translational velocity.

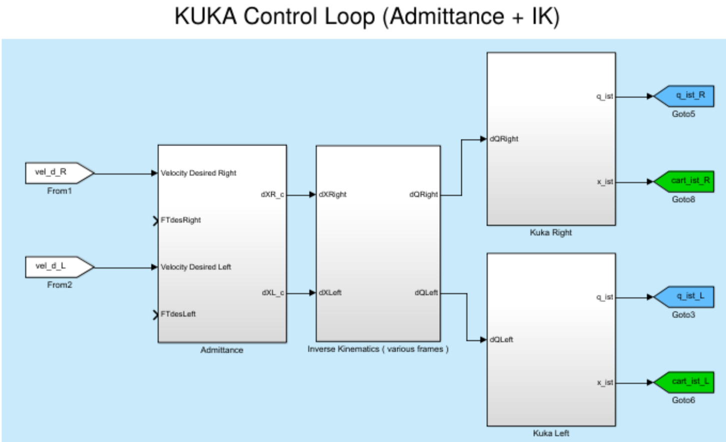


Figure 9. Impedance controller of the KUKA manipulator in MATLAB simulink

8. Experimental Analysis

For evaluating the experimental information, firstly we need to analyses the quantitative data which is collected during experimental procedure. The work is focused on different aspects of the task; precision; duration of task; Error between the commanded angles position and attained position in subtask-1. Distance of obstacles; radius of obstacles; angle between human and obstacle in subtask-2. The subtask-1 and suntask-2 tasks are conducted in three trails which is carrying an object from one place to another place with distance about half meter.

8.1. In Sub Task-1: The human guidance according to desired trajectory

The given desired trajectory is shown in Fig. 10(a) and conducted trails three times for each participant. All the participants are successfully finished the given trajectory task.
The desired trajectory contains nine (9) checkpoints and the distance between initial and final check point is given about the half meter in horizontally. The checkpoints are created in a sequential order to guide the human wrist. According to these points, the accomplishment of task is consider if and only if all the checkpoints are reached by the user in a sequential order. Nevertheless, the participant should cross all the checkpoints according to the given check point's numbering Fig. 10(a) in order to fulfillment the task. The guidance is directed towards the next particular checkpoint, this is done by calculated the vector direction and euclidean distance between the real-time human position and given check point and this process is repeated up to final checkpoint in sequential order. The directed angle is calculated to produce the vibrations according to the obtain directed angles.

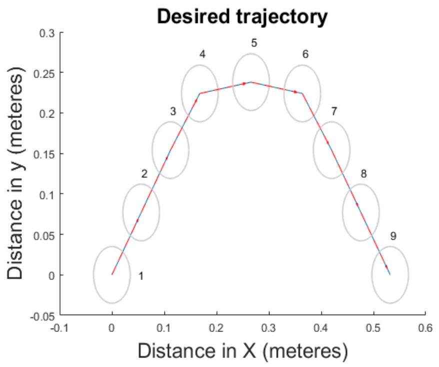
8.2. In Sub Task-2: The human-robot team obstacle collision avoidance in HRT

In this experiment the human would choose his/her own approach path from initial to final position. In the workspace we are introduced inadmissible area (i.e. obstacles or restricted area), this inadmissible area is invisible to human/user side.

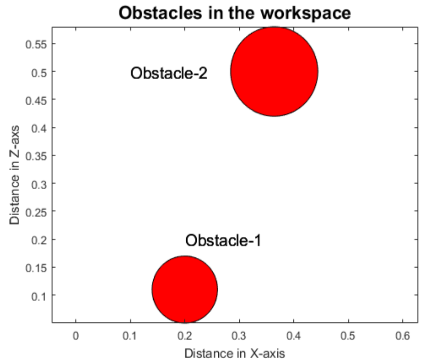
The initial and final position is declared (prior knowledge)to the user. Figure. 10(b) the red color circle shapes are declared as the obstacles/inadmissible area with radius $R_{obst_1} = 0.06m$ $R_{obst_2} = 0.08m$ for obstacle-1 and obstacle-2 respectively. In this experiment we consider as static obstacles and the evaluation of static obstacle would be similar for the dynamic obstacles. Nonetheless, our approach is based on a real-time calculated angles between the human and obstacles for producing the vibrations stimulus to WWB. Also, we are tested with a real-time dynamic obstacles (where the position of the obstacles are tracked by Qualisys system) and it is worked as well. However, the human can recognize by the real-time obstacle movements and might be disturb his/her with changing the real-time obstacles during the experiment. Therefore, for having a better evaluation of vibrotactile feedback, the obstacles are taken as static and invisible to the human side. The human could not see the obstacles but feel the vibrotactile feedback by WWB when the human position near to the obstacles. The vibration stimulus are given in this experiment as a repulsive, which guide the human/hand against the obstacles when the he/she in/near to the obstacle area.

8.3. In Sub Task-3: The robot singularities avoidance

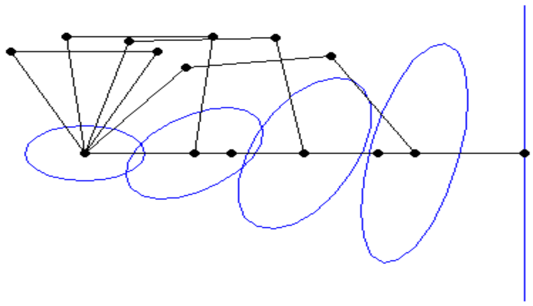
This experiment is showed about how the vibrotactile feedback guides the human when human desired motions/actions makes the robot singular configurations. We are calculating manipulability index volume at each time step in this experiment, where the manipulability index value (14) changes according to the human-robot cooperative manipulation movements. Due to the technical reasons, the robot singular configurations is not good to reach, mean while the human can reach near to the singular configuration of the robot. This strategy is done by taking the worst index value (i.e minimum threshold value of manipulability index volume), when the minimum threshold volume of manipulability index (14) the vibrotactile feedback is activated to give guidance to the human wrist. This guidance drives the human towards the maximum manipulability volume. such that, the human steers his/her desired motions according to high manipulability volume.
Indeed, the vibration stimulus are given in this experiment as a repulsive, which guide the human-robot desired motions against the robot singular configurations when HRT cooperative manipulation reaches to robot singularities.



(a) The designed trajectory for the subtask-1, where the trajectory contains nine check points in the workspace.



(b) The given circular obstacles with different radius in the HRT workspace



(c) The sample figure shows how the manipulability index volume changes with the robot manipulator arm movements, reaches singular configuration when the arm totally stretched. The blue ellipsoid represents the index volume, black color lines represents the robotic manipulator and black bold dots represents joints

Figure 10. Experimental sub-tasks plots for desired trajectory, obstacle in workspace and manipulability value

9. Experimental Results

This section is evaluated all the three obtained experimental results briefly. This work is more concentrated on how the vibrotactile feedback performance is useful to the user in pHRI team. During all experiments, the cooperative manipulation took place in a known environment, where the human operator is tracked via motion tracking system and his/her has visual feedback about the robotic manipulator.

In all three participants in this experiment, the **participant-1** ($\mathbf{p_1}$) and **participant-2** ($\mathbf{p_2}$) had not have any experience on the wearable wristband device tasks and vibrotactile feedbacks before. The **participant-3** has sufficient experience with wearable wrist device and participated in many other vibrotactile feedback experiments. In order to understand the better performance criteria of the VT human guidance in HRT, we are taken the 3 different participants from different backgrounds. To understand about the WWB device and vibrational directions, one free trail is conducted to all participants and this is not taken in to evaluation results. Subsequently, there is problem in this check point approach, if when the user miss any one of the check point and then our approach guides back to unfinished checkpoints, however no participant is missed the sequence of the checkpoints in use.

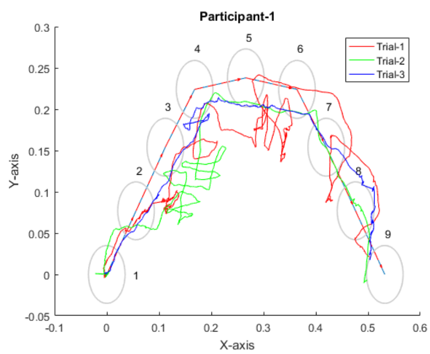
Figure 11(d) shows the duration of the time taken of each participant in three trials. However, the completion time of task is varied from participant to participant and trail to trail. The plot is showed the significant decrease of completion time from **Trail-1** to **Trial-3** of all participants. The **participant-3**($\mathbf{P_3}$) results are better than other participants. This results Fig. 11(d) represents the completion is better when then participant learns the task.

Figure 12(b) shows the mean distance of the human wrist position during the experiments. The average distance between the check point and human wrist is not much difference of all participants. However, the results are showed that, the deviation is not much high from desired trajectory, where the average distance between the checkpoints are 0.0948 m. The obtained results are closer to desired path in workspace.

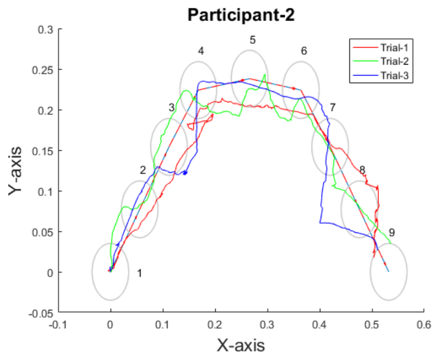
Figure. 12(a) describes the results of the mean error between the commanded angle and human attained angles which is scaled by 10 time steps due to noise and frequent changes in human position. Although still there is higher deviation between commanded angle and attained angle. A small change in human position or noise make different commanded angles.

9.1. *Results for Task-1*

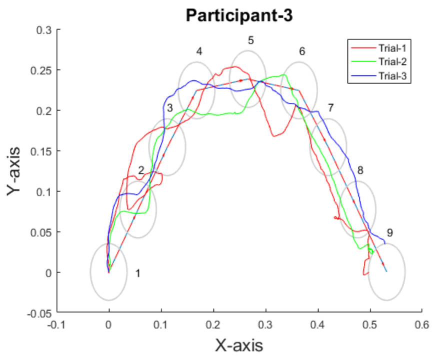
The three figures [11(a) 11(b) 11(c)] show the participants performance evaluation according to vibrotactile stimulus on the wrist. All the participants in all trails are fulfilled the goal position from initial start without much deviations from desired trajectory. In the figures 11(a), 11(b) and 11(c) the red, green and blue trajectories are plotted for $Trial_1$, $Trial_2$ and $Trial_3$ respectively.



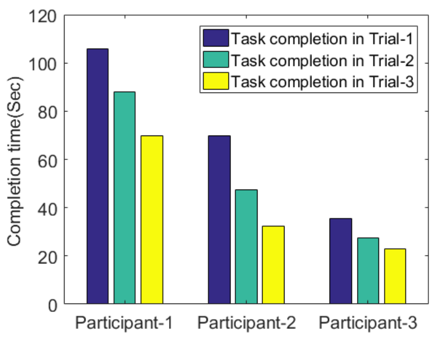
(a) The $Participant_1$ attained trajectories in the three different trials during the human guidance task.



(b) The $Participant_2$ attained trajectories in the three different trials during the human guidance task.

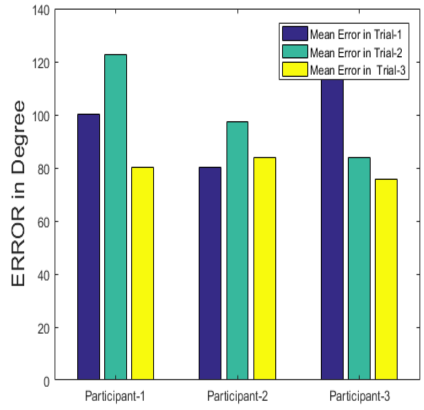


(c) The $Participant_3$ attained trajectories in the three different trials during the human guidance task.

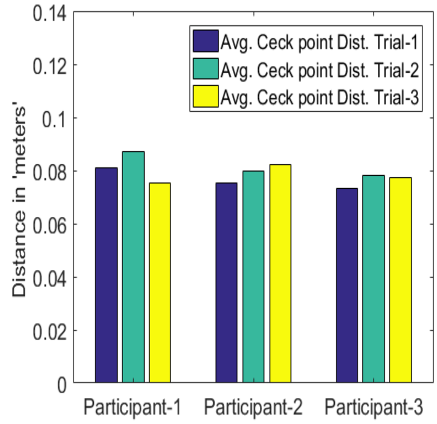


(d) Completion time of the participants in all experimental trials

Figure 11. Three participants' attained trajectories for three trails according to the desired trajectory and completion time for all trails



(a) Error of the attained human's position to guided position by wristband device



(b) Average distance between the desired trajectory and all attained trajectories during subtask-1 experiment

Figure 12. The human position and distance error are plotted according to the achieved data during subtask-1 experiment

9.2. Results for subtask-2

Figure. 13 shows that the participant has freedom to choose his/her own path from the initial to final position and vice-versa. The results are showed that, the human easily avoided the obstacles in the workspace by vibrotactile feedback though some of the human paths are collided the obstacle. Nevertheless, we are set (threshold distance) to generate the vibrotactile stimulus very near to obstacles for showing how VT feedback guidance precisely avoid the obstacles in practice. On condition that, the threshold distance plays important role for perfect avoidance. Although we are achieved better results and almost all the times when he/she reaches to the obstacles and the vibrotactile stimulus help to guide the human away from obstacles.

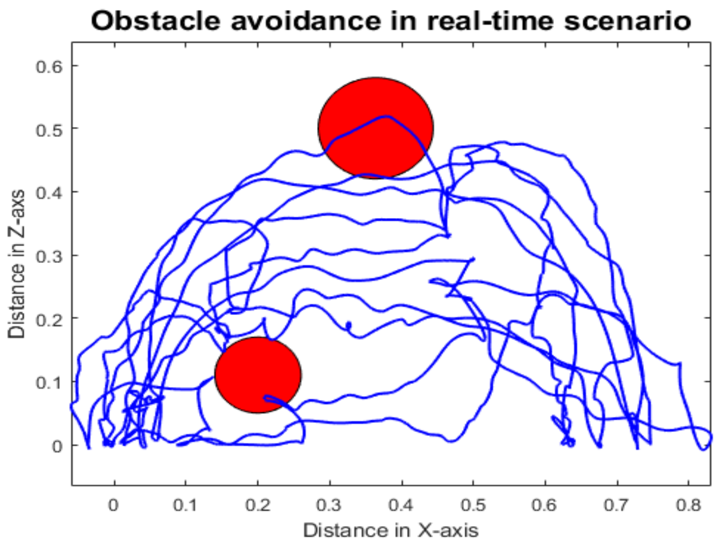
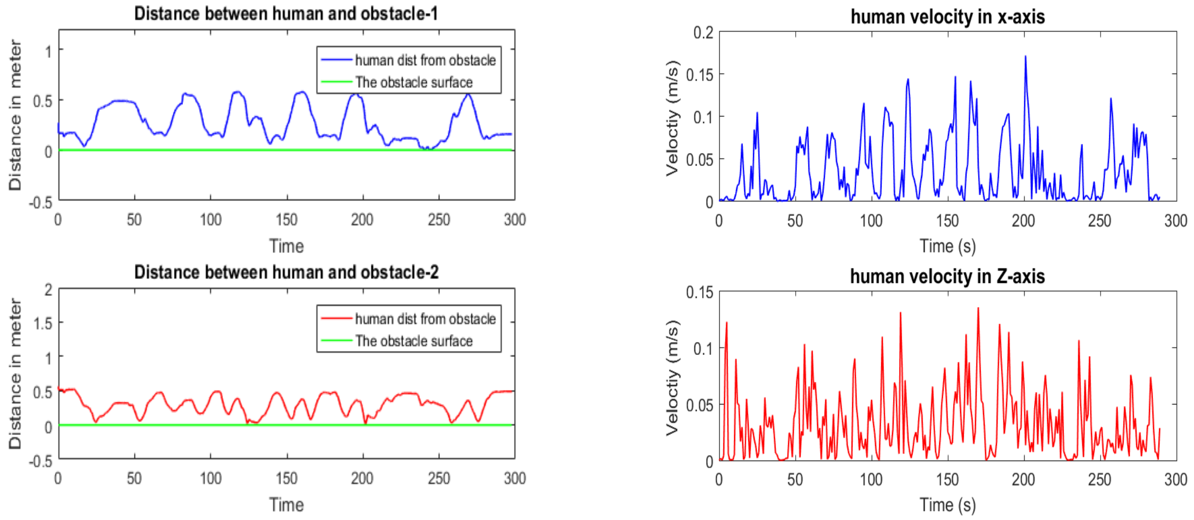


Figure 13. The human-robot team manipulation trajectories in the inadmissible area during subtask-2 experiment

Figure. 14(a) shows the distance of the obstacle-1 and obstacle-2 with respect to the human position. The blue color line and red color line indicate the distance between the human position to the obstacle-1 and obstacle-2 respectively. The green color line is plotted to represnts the obstacle's surface. The results show that, the penetration into the obstacles are eligible/ very low and achieved perfect avoidance by increase the threshold value for generating stimulus.



(a) Distance between the human and obstacle

(b) Velocity of the human during subtask-2 experiment

Figure 14. The distance between the human to the obstacle-1 and obstacle-2 at each time step with calculated velocity

We are changed the obstacle position and radius nonetheless the results are almost the same by changed parameters of the obstacles. However, the human's position does not collide/penetrate into the obstacles mostly. Almost all the time, when the human approaches to the inadmissible area the VT feedback helps the human to move into admissible area.

Figure 14(b) show the velocity of the human during subtask-2 (i.e obstacle avoidance in pHRI). The blue line and red line represents the velocity in human's X and Z directions respectively. The results in the Fig. 14(b) clearly seen the human velocity in **X** direction gradually goes to minimum when the human reaches to the obstacles/inadmissible area. Meanwhile, the robot is free to move according to the human desired velocity and the stiffness and friction of joints might be appose some amount human desired velocity, indeed this is an eligible affect.

9.3. Results for subtask-3

This section shows the evaluation results of the subtask-3, the manipulability index value Fig. 15 changes by human desired motions. The human has free to choose his/her desired motions in the workspace. The human velocity and position is changed according to the VT feedback guidance which are depicted in figure 16(a) and 16(b) respectively.

The index value changes according to the change of human-robot team position/velocities and also clearly showed in Fig. 15, this value represents the robot singularities, where the blue states the index value and red line shows the nearest (minimum) for robot singular configurations. The threshold value sets to active the VTF by WWB device, where this threshold value is nearest value to get robot singularities. The human desired motions drive to singular configurations the VTF clearly steers in the maximum capability direction.

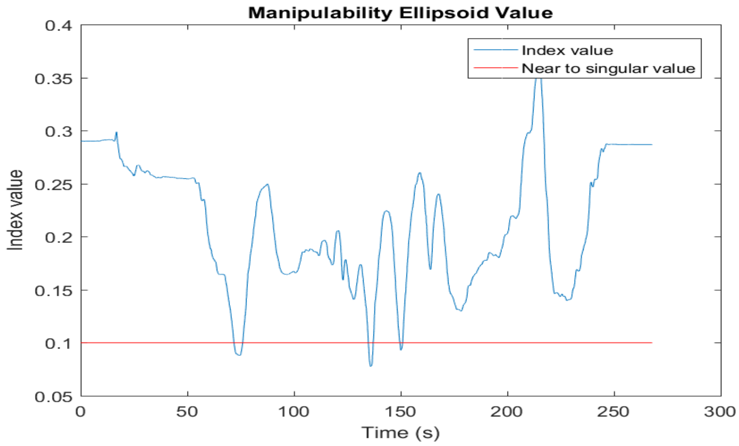
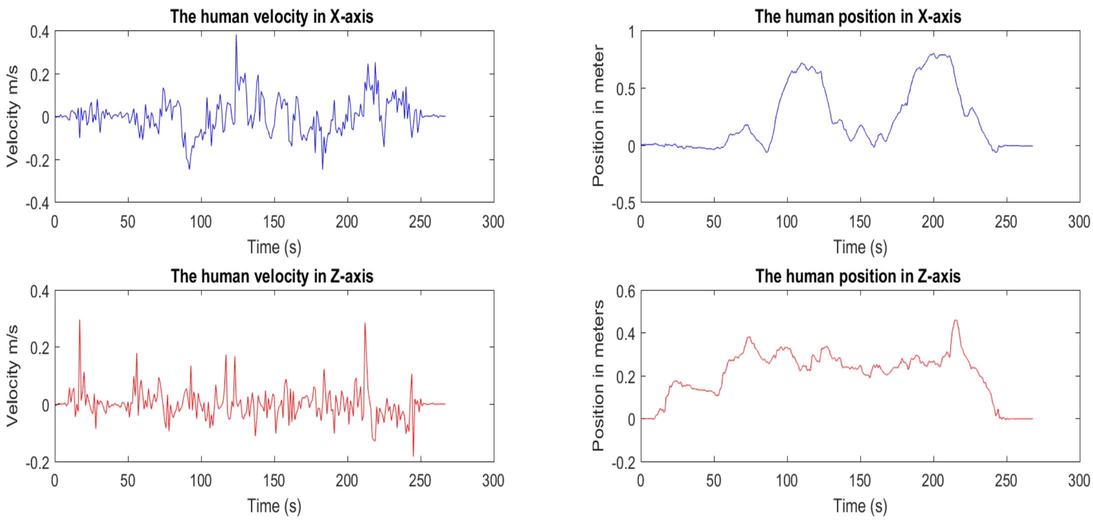


Figure 15. The manipulability index value during the human-robot cooperative manipulation

Figure 16(a) shows the human velocities according to index value and VTF guidance during the task. The singular is calculated in X-Z plane for the robot and user's velocities changes according to the commands send by WWB device.



(a) Velocity of the human during subtask-3 experiment

(b) Position of the human during subtask-3 experiment

Figure 16. The attained positions and velocities of the human during the subtask-3 experiment

Figure 16(b) states the position of the human according to the VTF commands. When the positions of the user is reached to the robot singular value then the WWB device gives commands into the maximum capability position space. Then the user is effectively driven the common (human-robot) object into robot's maximum capability space.
The results of the subtask-3 is showed that, the VTF guidance is easily steers the human in admissible area when the human desired motion goes to robot singularities.

10. Discussion

Our work is divided into three subtasks in oder to show the human guidance by vibrotactile feedback in direct physical human robot interaction. In the first part of work, all the participants are successfully accomplish the given task , though considerable deviations take place from desired trajectories and desired guided angles. This issues can be solved by increasing the number of check points with decreasing the checkpoints radius. In spite of some of the deviations, the aim of the experiment is fulfilled and showed the vibrotactile feedback as good efficiency at high level tasks which useful in industrial/commercial physical human-robot interaction purpose. The test has proved that, the human guidance in physical human-robot interaction is possible and useful for intuitive HRI. Subsequently, the participant is gradually decreased the completion task time from trail to trail. This shows that, the VTF helps the human to learn the desired trajectories in short period of time. Furthermore, all these evaluation give sufficient information of human guidance has very good behavior in high level tasks (i.e human-robot interaction tasks.)

Second part of the work shows that, the VTF not only use for human guidance towards the desired trajectory in pHRI, but also showed for pHRI obstacle avoidance. After evaluating all the participants only few times at the beginning of the task, the partial collision take place with obstacles. Nonetheless, all the time during the experiment task the participants easily avoided an inadmissible area without any failure. In our obstacle avoidance approach, we are used repulsive vibrotactile feedback against inadmissible area. In this experiment, we are measured real-time human-robot velocity along side of human-robot position and distance of obstacles. Subsequently, the human-robot distances are almost all the time is greater than zero, (where the zero values says the obstacle surface). Apart from, the human-robot team considerably changed the velocity during experiment task and more specifically the velocity goes to minimum when the participant reaches closer to obstacles. Consequently, the evaluation results clearly proved that the vibrotactile feedback easily guided the human to get way from inadmissible area and avoided in obstacle collision.

Finally, the third part of the work is also given good results for human-robot singularities avoidance. The whole scenario is depends of the manipulability value ((14)) and robotic manipulator Jacobian matrix. Here, we are calculated the maximum vector where the human gets a good index value. Later this vector is used for calculating the directional clues and sends this clues commands via WWB device. Of course, during this experiment human has free to choose to any manipulation task and when the human stretches the robotic manipulator totally or drives to inadmissible area. The VTF guidance activates to give the clues in the admissible area with help of WWB device.

11. Materials and Methods

The robotic manipulator are 7DoF KUKA LWR 4+ lightweight robots, Qualisys camera system, vibrotactile feedback system (University Of Siena, Italy), rectangular cuboid with $3kg$, hand glove and markers. Experiments was carried in real-time and data collected in real-time. Matlab software was used to interpretation of data and plots. This work was involving humans, which was taken by the help student volunteers.

12. Conclusion

In this work, the vibrotactile feedback for human guidance in physical human-robot interaction when manipulating a common object is investigated. The human-robot team is commanded by a vibrotactile stimulus that is equipped with a wearable wristband haptic device that transfers information about the task to the human. The cooperative manipulation took place in a known environment where the human operator is tracked via motion tracking system and have visual feedback about the robotic team. Three different subtasks are evaluated in this work and the results are effectively achieved. All the subtasks are successfully finished by the user's during the experiments.

The experiment results shows that, the human motion guidance by vibrotactile feedback is effectively consider in the complex task like direct physical human-robot interaction task, where the VT guidance is able to solve some problem in the field of the direct human-robot interaction. Our approach has proved many results and might useful in the research field of haptics (vibrotactile feedback) and human-robot interaction further. Hence our work shows that, the vibrotactile is given good results in human-robot interaction research.

Significantly, along side of all the postulates there is some limitations in our work and those are stated in the following

- During the human guidance in one of the subtask, there is quite measurable deviations from desired trajectory where is not effectively perceive the vibrations commands;
- During the human guidance in obstacle avoidance, also sometimes the users are collide with obstacles with little confusion of VTF guidance in high complex task.

13. Future work

Future work will extended by evaluating the previous framework using more than one robot manipulator and one user for having a larger human-robot team. Also, by increasing the number of the users for the user-study in all subtasks might be can get more effective solution for industrial/hight level environment. Although, the vibrotactile feedback is implemented for getting the effective kinematics and dynamics estimation parameters in physical human-robot interaction field, nonetheless more work to be done for implementing this approach in practically. Finally, all the subtasks which evaluated in this work could combined together for more intuitive direct physical human-robot interaction.

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Author Contributions: In this work, Aggravi, Marco and Salvietti, Gionata and Prattichizzo, Domenico their vibrotactile feedback concept and device is helped to implement this concept in the direct physical human-robot interaction field. Their methodology is helped to perceive feedback to the human in our experiments 9.
Mörtl, Alexander and Lawitzky, Martin and Kucukyilmaz, Ayse and Sezgin, Metin and Basdogan, Cagatay and Hirche, Sandra research in direct physical human-robot interaction was motivated to my work and this work was based on their concept 4.

Conflicts of Interest: The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CM	Cooperative Manipulation
DOF	Degree of Freedom
HF	Haptic Feedback
HRC	Human-Robot Collaboration
HRI	Human-Robot Interaction
HRT	Human-Robot Team
MI	Manipulability index
MRT	Multi-Robot Team
ME	Manipulability Ellipsoid
pHRT	physical Human-Robot Team
pHRTI	physical Human-Robot Team Interaction
SVD	Single Value Decomposition
VT	Vibrotactile
V	Visual
VF	Visual Feedback
VM	Vibro-motors
WB	Wristband
WBD	wristband Device
WWBD	wearable wristband Device
WHD	Wearable-Haptic-Device
W	Manipulability Measure Value
P_1	Participant-1
P_2	Participant-2
P_3	Participant-3
R_{obst_1}	Obstacle-1 Radius
R_{obst_2}	Obstacle-2 Radius

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